MATERIAL CHOICES FOR FIBRE IN THE NEOLITHIC: AN APPROACH THROUGH THE MEASUREMENT OF MECHANICAL PROPERTIES.

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ABSTRACT

Studies of the Mesolithic-Neolithic transition in Europe have focused on plants and animals exploited for food. However, the exploitation of plants for fibres underwent a significant change with the addition of domestic flax as a fibre crop. While the technology of flax fibre processing is increasingly understood by archaeologists, its material value as a fibre crop in comparison to indigenous fibre is less well explored. We examine the mechanical properties of flax and two indigenous fibres (lime bast, willow bast), by testing fibre strips for tensile properties and discuss the results in the light of material choices in these periods.

Keywords: Mesolithic-Neolithic Transition, material properties, fibre, flax, lime, willow, textiles.

INTRODUCTION

As one of the major horizons of change in European prehistory, the Mesolithic-Neolithic transition has been extensively studied (recently Bickle & Whittle 2014). The nature of this transition is defined by the introduction of domesticated plants and animals and their role in agriculture. While archaeologists have debated the reasons and effect of these changes (see overviews Barker 2006, 1-38; Robinson et al. 2011), the focus of research has been mostly on food resources and their role in diet. However plants and animals are also a source of materials and Neolithic / Mesolithic communities procured plant fibres for their tying, binding and fibrous cloth needs (Hardy 2008; Hurcombe 2014, 36-42). The Neolithic in Europe saw a major change in the source of plant fibres with the introduction of flax as a domesticated fibre plant from southwest Asia (Zohary et al. 2012,103-6), that was used alongside indigenous plant fibres such as tree bast, which is extracted from the inner bark of certain trees, and other indigenous plant species.

This changing picture of plant fibre resources does not just represent a different mode of subsistence or technology of production by early farmers, but a whole new material whose properties could have been understood through experience and experimentation. When considering the role of fibres in the Neolithic, this raises the question; why did early farmers choose to grow flax for fibre? Was it because flax fibres provided an especially good material that was superior to alternative fibres? In this paper we address this question from a materials perspective through measuring the mechanical properties of flax, lime and willow bast fibres. In the light of the many variables affecting natural fibre properties, this constitutes an initial study and further factors influencing fibre properties are considered in the discussion.

The recent materialist turn in archaeology with its schools of thought around materials, materiality, material agency and symmetrical archaeology, stems from an epistemological desire to understand the complex relationship between people and things. Within this debate is the investigation of archaeological materials through their material properties. This has been proposed in different veins by Jones in his paper "Archaeometry and Materiality" (2004), and Ingold "Materials against Materiality" (2007) both of whom have been criticised (e.g. responses to both papers). As Lucas observes, Ingold and Jones are attacked for their physical view of materiality, their attention to 'brute matter', for holding a vulgar notion of physicality, and with it, accusations that this separates mind and matter, nature and culture (Lucas 2012, 162-4). While justified, Lucas also notes, archaeologists face difficulty in marrying physical and social concepts of materiality.

To reject the physicality of matter is counterproductive to investigating materials, as this is part of the choices people face as they transform materials into objects which in turn affects the relationships people have with objects. As recognised in textile technology, fibre is the smallest unit of finished products such as thread, cord or textile and is its primary material (Collier and Tortora 2001,29,47). Hence fibre properties influence the characteristics of these products, whether mechanical, aesthetic or sensory and in turn the ideological, political and social aspects these engender. Archaeologists are frequently dealing with uncommon materials (e.g. lime bast, willow bast) that few non-specialists have encountered. A range of perspectives, including one of physical matter is required to consider a material's role in the past. The purpose of this study is to add new quantitative, comparative data (of flax and two species of tree bast) to this literature and through this question the material choices provided by these fibres and hence the relationship between people and fibres in the Mesolithic and Neolithic.

Understanding fibres is not helped by the nature of the archaeological record as when ancient fibre artefacts such as threads, cords, rope, textiles and basketry are excavated they are fragile, degraded and no longer retain their original material properties. For this reason, mechanical testing in this experiment was carried out on modern fibre strips of the same species (Figure 1). Furthermore, commercial fibres used in the modern textile or craft industry are industrially processed to speed up and stabilise the process and remove all extraneous plant matter (Jarman 1998,17). In this experiment the plant materials were processed by hand using methods appropriate to Mesolithic and Neolithic technological contexts. Modern examples of these fibres prepared as fibre strips are here tested for tensile properties: Young's Modulus, ultimate tensile strength and toughness. These tests characterise the elasticity, strength and amount of energy required to deform and break the materials. The value of mechanical testing is that it provides objective, quantifiable and comparable results, and may be used to predict the performance of materials (Saville 1999,3).

Figure 1. Fibres tested: clock wise from bottom left: lime bast, willow bast, willow bast boiled, flax and raffia (photo Susanna Harris).

PLANT FIBRES IN THE MESOLITHIC AND NEOLITHIC

Resources

Bast fibre is the term given to those fibres extracted from plant stems, whether annual plants or the inner bark of trees. This experiment was set up to study the mechanical properties of bast fibres of flax, lime and willow processed by two methods. These are three of the most commonly identified fibre species from Mesolithic and Neolithic contexts.

Flax. While taphonomic processes make Neolithic fibres difficult to study, recent research has refined questions around the domestication of flax (Allaby et al. 2005), flax processing technology (Herbig and Maier 2011; Leuzinger and Rast-Eicher 2011; Maier and Schlichtherle 2011) and chronology of flax cultivation in Europe and southwest Asia (Karg 2011a; Zohary *et al.* 2012, 103-6). Along with other domestic crops, flax was one of the founder crops of the Early Neolithic originating in southwest Asia (Zohary *et al.* 2012, 104) and was the earliest cultivated fibre plant in Europe. Discounting claims for Palaeolithic flax fibres (Kvavadze et al. 2009) on the basis of the points outlined by Bergfjord et al. (2010), the earliest preserved identified linen threads and cloth are found in southwest Asia, for example at Nahal Hemar, a desert cave in Israel, from which a twined cloth is radiocarbon dated 7065 cal. BC (8500 ± 220 BC with 95.4% certainty. OxA 1015, Calibrated with OxCal 4.2) (Schick 1988, 31). In Europe, besides scattered finds the largest concentrations of fibrous artefacts are from the waterlogged Late Neolithic lake settlements and wetland sites of the circum-alpine area (c.4200 to 2800 cal.BC) and include threads, cords, nets and textiles made from flax and tree bast (for example: Bazzanella *et al.* 2003; Bazzanella and Mayr 2009; Karg 2011b; Körber-Grohne and Feldtkeller 1998; Leuzinger 2002, Médard 2010; Rast-Eicher 1997, 2005) (Figure 2a & 2b). This is several thousand years later than the earliest preserved flax seeds in the alpine region and central Europe, which date to the end of the 7th and 6th millennium BC (Rast-Eicher 2005, 119). This highlights a problematic lacuna in evidence.

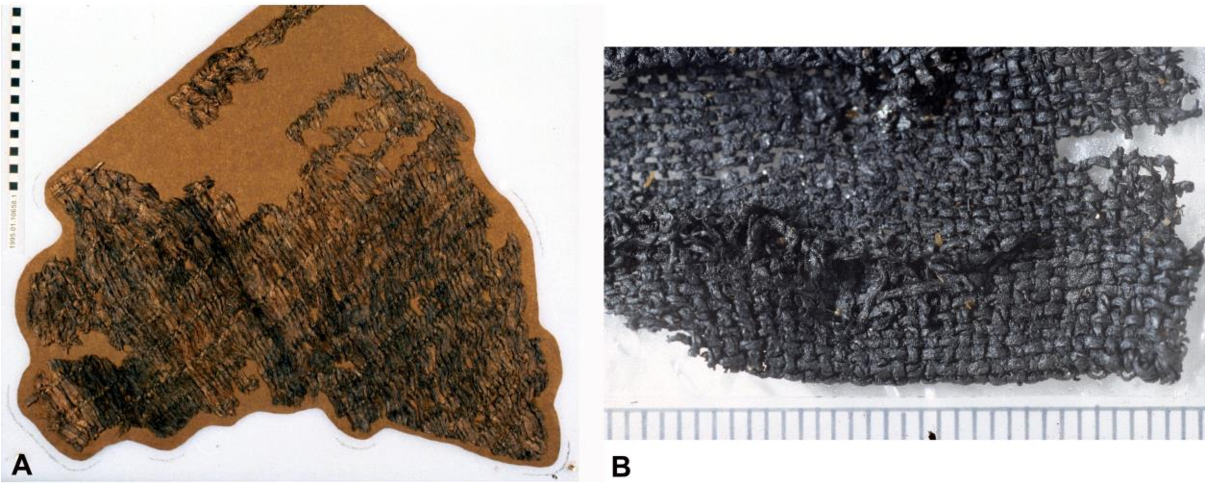

Figure 2. A: Twined cloth in lime bast (*Tilia sp.*) from Arbon Bleiche 3, Switzerland, dendrochronology dated 3384-3370 cal. BC. Thread diameter in passive element 3mm, scale in cm. B: Textile most likely linen (*Linum sp.*) from Arbon Bleiche 3, Switzerland. Scale in mm (Photo: Amt für Archäologie Thurgau, www.archaeologie.tg.ch, Daniel Steiner).

Tree bast. Knowledge of the species exploited for indigenous plant fibres rests on the identification of preserved fibres, as tools are rarely associated with these fibres and archaeobotanical remains are insufficient evidence for fibre extraction. Tree bast fibre artefacts only survive in favourable conditions, such as dry, cold or waterlogged environments. Preserved threads, cords, nets and looped cloth from Late Mesolithic contexts in northern Europe provide rare evidence for the raw materials used by hunter-gatherers for plant fibres. Of these, tree bast fibres from the inner bark of certain species of trees and grasses were a key resource. Willow (*Salix* sp), possibly poplar bast (*Populus sp*.) and grasses (Gramineae) are identified in looped cloth, cords and fish nets from submerged Mesolithic sites in Scandinavia and around the Baltic (c. 4200-3400 cal.BC) (Andersen 2013, 215-6; Bender Jørgensen 1990, 2; Burov 1998, 58-62). In the Late Neolithic Swiss Lake Dwellings, tree bast fibres were of lime, oak and willow (Médard 2010, 57). These trees are part of the indigenous, deciduous forests of Europe (Greig 1982, 23).

Other plant fibres It is possible that bast from other plants was used for fibres, although at present few of these species have been identified in Mesolithic or Neolithic artefacts. This is potentially an issue of preservation and identification. Bulrush fibres are identified at Zamostje 2, a Mesolithic to Neolithic site in Russia (Lozovskaya et al. 2012). Other indigenous fibrous plants that could have been exploited for fibres, fibrous leaves or stems, include but are not limited to: wild clematis (*Clemetis vitalba*), bramble (*Rubus fruticosus*), honeysuckle (*Lonicera L.*), moss (*Polytrichum commune*) flag iris (*Iris pseudacorus*), cat tail or reedmace (*Typha sp.),* club rush (*Scirpus lacustris*), soft rush (*Juncus effuses*) and nettle (*Urtica dioica*) (Harris & Gleba 2015, Hurcombe 2007,122; Médard 2012, 368; Wood 2011, 13). Reeds, virburnum and grasses were used as whole stems (Rast-Eicher 1997,302). Nettles are assumed to have been exploited for fibre in the Mesolithic and Neolithic due to the abundance of seeds and mention in ethnobotanical sources (e.g. Hurcombe 2014, 55-7,63; Van Gijn 2010, 63, 85). However, nettle is not included in this study as the authors know of no Mesolithic or Neolithic fibre artefacts identified as nettle; the earliest identified nettle fibres are from the Bronze Age (Barber 1991, 19-20; Bergfjord et al. 2012; Farke 1991). Wool from domestic sheep was only used for textiles from the mid 4th millennium BC in southwest Asia, and substantially later in many areas of Europe and is therefore of later chronological concern.

Processing

Plants (annuals or trees) require processing to extract the bast fibres following a range of techniques. It is often difficult to ascertain the exact methods used to process fibres in the past.

Flax. For many decades it was assumed that in prehistory flax stems were processed for fibre according to the techniques of rotting (*retting*), beating (*breaking*), scraping (*scutching*) and combing (*heckling*) (Barber 1991, 13-4; Martial and Médard 2007, 70-4), which were historically widespread in Europe and beyond (Jarman 1998, 10-9). Retting softens the fibres and rots the connective tissues of the plant matrix. Beating breaks the inner core of the stem, while the combination of beating, pounding, scraping and combing act to remove the unwanted tissues and inner core as well as separate out the fibres. Historically, and in small scale production in the present day, the techniques and combination of processes can vary. Retting, for example, may be achieved when whole stems are submerged in pits, in natural water (fresh, brackish, salt) or left to lie in fields where the action of dew rets the stems (Jarman 1998, 10-19).

Observation of preserved flax fibres used to make threads and textiles in prehistoric Europe suggests that the plants may have been processed differently. Microscopic investigations of Neolithic flax fibre products from the lake dwellings demonstrate less thorough processing: extraneous plant matter is left on the fibres, and fibres remain in bundles (Körber-Grohne & Feldtkeller 1998, 153; Leuzinger & Rast-Eicher 2011,537, 540; Rast-Eicher & Thijsser 2001; Maier & Schlichtherle 2011, 569-70). It seems likely flax was processed with a light ret before stripping the fibres from the stem (Leuzinger & Rast-Eicher 2011,538-9).

Tree bast. Methods of tree bast processing are understood from ethnographic sources, especially from Scandinavia, the Baltic countries, Russia and central Europe where historically lime bast was an important fibres for rope and cord making (Crawford 2005; Dimbleby 1978; Granlund 1943;Hanssen and Lundestad 1932; Hodges 1995, 127; Hurcombe 2014, 30; Myking et al. 2005,66-69; Pigott 2012,350, Warnford 1880, 916-917). These sources report four methods of processing lime bast. 1) Branches are removed from the trees in early summer, just as the leaves grow to full size. Either the whole branches or stripped bark are then soaked in fresh or sea water for several weeks (*retting*), which softens the bast and causes the separation of individual fibrous layers. 2) Bark is removed earlier in the year when the sap is rising in the tree, in which case the bast can be separated directly from the outer bark. 3) Trees are cut in winter and smoking the branches in an oven for a full day. In the second and third method no retting is involved, the fibres are directly processed and remain stiffer than the retted fibres gained in the first method. 4) Stems or inner bark are boiled in a wood ash solution (weak alkali) to separate the fibres.

These techniques are reported as potential methods used in the past (Körber-Grohne & Feldtkeller 1998, 157; Médard 2003, 82; Rast-Eicher 1997, 302-3; Reichert 2000, 2007). It remains difficult to ascertain the exact method of processing tree bast from the archaeological evidence. For example, threads, cords and textiles which are washed or used in wet environments continue to slowly rot throughout their use life (Hero Granger-Taylor pers.comm) and may appear more thoroughly retted than was originally the case. Tools are poor indicators of tree bast processing. Use wear analysis on Neolithic stone tools suggests they were used to scrape plant fibres from dried stems (Van Gijn 2010, 87-8). Similarly, Neolithic bone tools may be associated with removing bark from trees (Médard 2003,82).

Properties

The study of the mechanical properties of materials is a developed area of materials science. Most research into plant fibres concentrates on those fibres with commercial value, such as flax (e.g. Airoldi 2000; Needles 1981; Puliti 1987; Kornreich 1952; Norton et al 2006; Wulfhorst 2001). Tree bast has been less frequently studied. In terms of quantitative analysis, a recent forestry report focused on the mechanical properties of a 12mm three-ply cord of lime bast (Troset and Aunrønning 2003 reported in Myking et al. 2005) and Pigott quotes stress at break for strand of *Tilia cordata* of 4.5kg mm^{-2} (44Nmm $^{-2}$), although with no reference to the source or methods (Pigott 2012,29-30). Ethnographic, historical and archaeological reports provide a qualitative approach to the mechanical properties of tree bast (Dimbleby, 1978, Granlund 1943; Hanssen & Lundestad 1932; Harris 2010; Hurcombe 2014,30; Medard 2003, 2010, 145; Pigott 2012, Rast-Eicher 1997, 303; Reichert 2007; 2013; Wood 2011, 12-14). Historical records record the suitability of tree bast fibres for tasks, for example lime bast rope in medieval shipping, and sacks, shoes and sails in eighteenth to mid-nineteenth century Russia and the Baltic (Körber-Grohne & Feldtkeller 1998, 156-57; McGrail 2014,204-51).

MATERIALS

We begin by clarifying the archaeological use of the term ‘fibre’. In the textile industry fibre refers to the long, fine, flexible units that form the basis of textiles which have a high ratio of length to thickness (Greaves and Saville 1995, 1). Typically they are considered to have a length at least one hundred times their diameter (Collier et al. 2009, 4). For materials scientists there remains an expectation that a fibre will be 100 microns or less in diameter. For archaeologists working with textiles, the term fibre refers to long, pliable raw materials that can be worked into thread and fabric (Gleba and Mannering 2012,5). This frequently refers to materials that are several millimetres in width and hundreds of millimetres in length. These are not fibres in the textile or materials science sense in that they include fibre bundles and extraneous plant matter; they are better described as fibre strips. In this experiment we work with fibre strips, as this was deemed appropriate according methods used to process fibres in the Mesolithic and Neolithic as discussed above. We refer to our samples as fibre strips.

Following the observations described above, that flax fibres appear to be less thoroughly processed in the Neolithic than the present day, the flax fibres in our experiment were removed from the dried, unretted stem in strips which were harvested in September when the seeds were ripe (Table 1). This is an important distinction for the tests carried out in this experiment, as it is frequently the single fibres of annual plants which are tested for mechanical properties in the commercial literature (e.g. Bodros & Baley 2008, 2143-4), or those mechanically processed fibres (e.g. Norton et al. 2006, 17), whereas we are interested in the fibre strips. The extent to which flax was retted in the past is unclear; here we chose to leave the fibres unretted.

Table 1. Source of fibres used in tests and method of processing.

The lime bast was extracted by removing the bark from the wood in July. The bark was water retted for six weeks, then separated into single layer strips which were then dried and split into finer fibres (Table 1). The willow bast was processed by two methods. Once the bark was removed in June it was dew retted for two months: half was stripped while dew-damp, the other half was boiled in a weak alkali solution. We tested commercially purchased raffia to provided a commonly available comparative example.

METHOD: MECHANICAL PROPERTY MEASUREMENTS

The fibres, prepared in strips, were tested for their tensile properties: Young's modulus, ultimate tensile strength, and toughness. Such plant materials are naturally inhomogeneous so ten tests were performed for each sample, on ten separate fibre strips of the same processed batch. The materials were tested under wet and dry conditions.

Tensile testing of the fibre strips was performed using an Instron Universal Tensile Testing Machine in the laboratory at the School of Materials, Manchester University which is maintained at a constant temperature and humidity. In preparation for testing, ten fibre strips of each sample were cut into fixed 100 mm lengths. The width of each fibre strip was recorded in millimetres and the thickness measured using a micrometer. The mass of each fibre strip was measured in grams using a balance. As these natural fibres are inhomogeneous, multiple tests must be carried out to gain a statistically reliable result (Saville 1999, 18). In these tests, ten fibre strips were tested for each fibre. Each fibre strip was placed in the Tensile Tester with an initial distance of 50 mm between the grips, and a continuous force was applied to stretch the fibre strip to failure. The tests were carried out according to standard procedures (see Saville 1999, 115-67,) and the force-distance curves recorded for each sample. From these force distance curves it is straightforward to determine the fibre strip's Young's modulus, ultimate tensile strength and toughness as discussed briefly below.

The properties of fibres, especially natural fibres, can be strongly affected by moisture content including atmospheric moisture content (Saville 1999, 26-8). The fibre strips were therefore tested under wet and dry conditions. The fibre strips tested in the 'dry' condition were measured after storing in the same humidity controlled room as used for testing for more than 24 hours. The 'wet' condition samples were soaked in water for five days. Each 'wet' tested sample was taken out of the liquid immediately prior to tensile testing with excess liquid being removed using an absorbent blotter.

Fibre	***Source***	***Latin name***	***Location (co-ordinates)***	***Harvesting***	***Retting***	***Fibre processing***
Flax	Linseed plants	*Linum usitatissimum*	West Sussex, UK. (51.031854, -0.311115)	Plants pulled in September when seeds ripe. Whole plant dried.	Stems not retted.	Stems snapped, woody core removed by hand. Bast fibres striped from stem.
Lime bast	Lime tree	*Tilia europaea*	London, UK (51.522331, -0.068257)	Branches pruned in July. Bark stripped when partially dried.	Bark strips water retted in pond water for 6 weeks.	Bast peeled from outer bark while wet and separated into individual layers, then into fibre strips.
Willow bast	Willow tree	*Salix sp.*	London, UK (51.601000, -0.047709)	Bark removed in June from freshly felled tree.	Bark dew retted slowly for 2 months.	Bast peeled from outer bark while damp and separated into fibre strips.
Willow bast boiled	Willow tree	*Salix sp.*	London, UK (51.601000, -0.047709)	Bark removed in June from freshly felled tree.	Bark dew retted slowly for 2 months.	Bast peeled from outer bark while damp, boiled in weak alkali solution to 10 mins, then separated into fibre strips.
Raffia	Palm leaf fibre	*Raphia farinifera*	Unknown	Unknown	Unknown	Unknown. In standard procedure the membrane on underside of leaf is peeled off, then separated into fibre strips.

Table 1. Fibre strips used in tests, source and processing method. All processed by S.Harris except raffia, which was purchased from a craft shop.

Young's modulus

Young's modulus (also known as the tensile modulus or elastic modulus) refers to how much the fibre will stretch elastically (deform) when a tensile force is applied. It therefore measures the resistance to extension, in other words the stiffness of the material (Saville 1999, 122). Young's modulus is measured in gigapascals (GPa or kN/mm^2). A fibre with a low resistance will stretch considerably when a low force is applied, for example a rubber band has a low Young's modulus (Collier & Tortora 2001,53). Materials with a high modulus tend to be brittle (i.e. stiff) regardless of tensile strength. The amount a fibre stretches or deforms is important as materials are usually used well below their breaking point. The Young's modulus is determined from the gradient of a straight line in the steep elastic (low elongation) region of the force-distance curve (below the yield point).

Ultimate Tensile strength

Generally described as the strength of a fibre, the ultimate tensile strength can also be referred to as the breaking strength or tensile strength at break. It is the "maximum tensile force recorded in extending a test piece to breaking point" (Saville 1999, 116). Ultimate tensile strength is measured in megapascals (MPa). Breaking force is proportional to cross sectional area; so although a spider's web is one of the strongest fibres, it breaks more easily than a human hair on account of its lower diameter (Collier & Tortora 2001, 52). Normalising the breaking force for each fibre by its cross sectional area gives the ultimate tensile strength.

Toughness

Toughness measures the amount of work required to break the material and can be calculated from the area under the force-distance curve. Toughness is measured in joules per cubic metre (J/m^3). In practice toughness measures the ability of the material to absorb energy and withstand shocks before catastrophic failure. This is particularly important for situations where sudden shock may occur, such as with car seat belts or climbing ropes (Saville 1999,127).

RESULTS

The measured values for Young's modulus, ultimate tensile strength and toughness for the fibre strips measured are shown in Figures 3-5. The error bars represent 95% confidence intervals and indicate the range of the results across the 10 repeats. Despite the issue that processing is likely to affect the properties of the fibre strips, variation between differently processed willow bast fibre strips was minimal in these tests. The greater differences were observed between species.

Fibre Strip Young's modulus

The measurements for the fibre strips' Young's modulus, measured in the wet and dry condition (lime bast, willow bast, willow bast boiled, raffia and flax) are presented in Figure 3 . Dry flax has the highest modulus (18 GPa) showing it has the stiffest fibre strips although the stiffness decreases dramatically for wet flax which has a far lower modulus of just 3GPa, so is more easily deformed, i.e. flexed. Indeed, all the fibre strips appear less stiff when wet so are more easily deformed in the wet condition. Boiled willow bast fibre strips show the smallest stiffness variations for the wet and dry conditions with both giving Young's Modulus values of less than 2 GPa.

Fibre Strip Tensile strength

Figure 4 shows the ultimate tensile strength measured for each of the fibre strips and the trends observed are similar to those seen for Young's modulus. Dry Flax has by far the greatest tensile strength at 350 MPa but this value decreases significantly for wet flax which has an ultimate tensile strength that is similar to the wet and dry values for the other natural fibre strips considered here. The other fibre strips also show lower tensile strengths when wet compared to when dry with the exception of boiled willow bast which has a similar low strength in both wet and dry conditions.

Fibre Strip Toughness

The toughness results for the fibre strips are shown in Figure 5. Some of the errors bars for these measurements are relatively large; however we can still draw some useful information from this figure. Dry flax produces the toughest fibre strips, with a lower toughness when wet. Lime bast and raffia also appear to be tougher in the dry condition whereas the two willow basts appear to have slightly greater toughness in the wet condition. In combination with the results for Young's modulus we can say that most of the plant fibre strips are both more pliable and weaker when wet, meaning they cannot be treated roughly when wet.

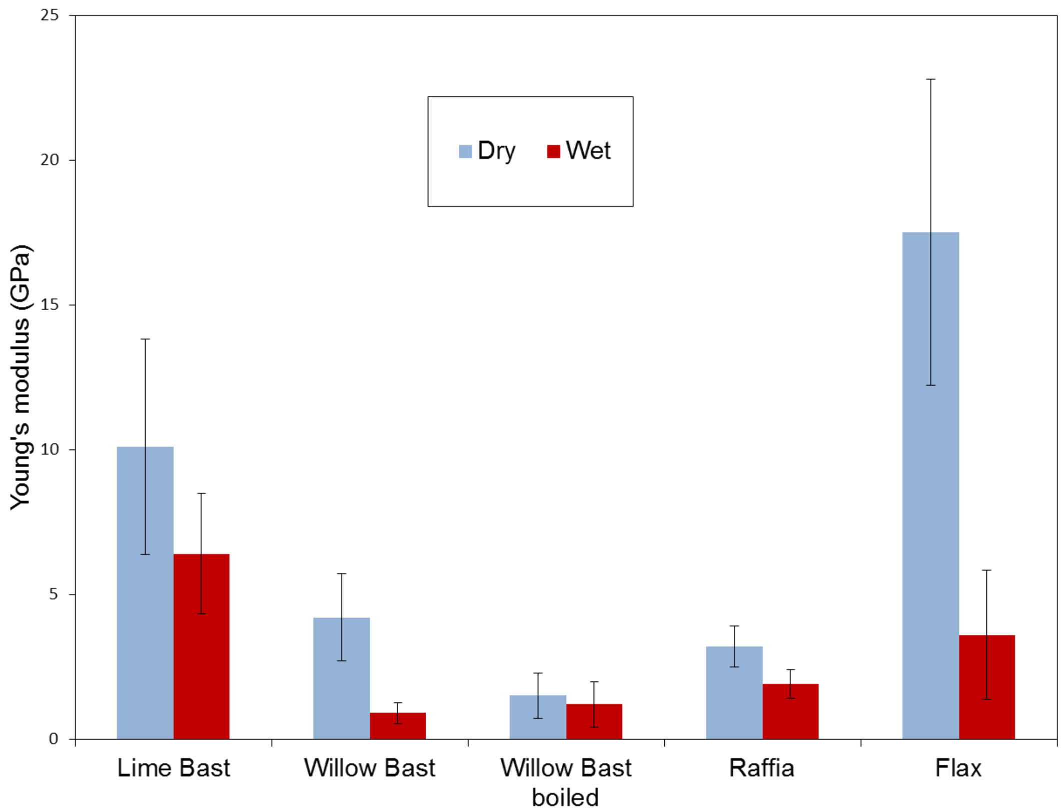

Figure 3. Comparison of the Young's modulus for the different fibres tested in 'wet' and 'dry' conditions.

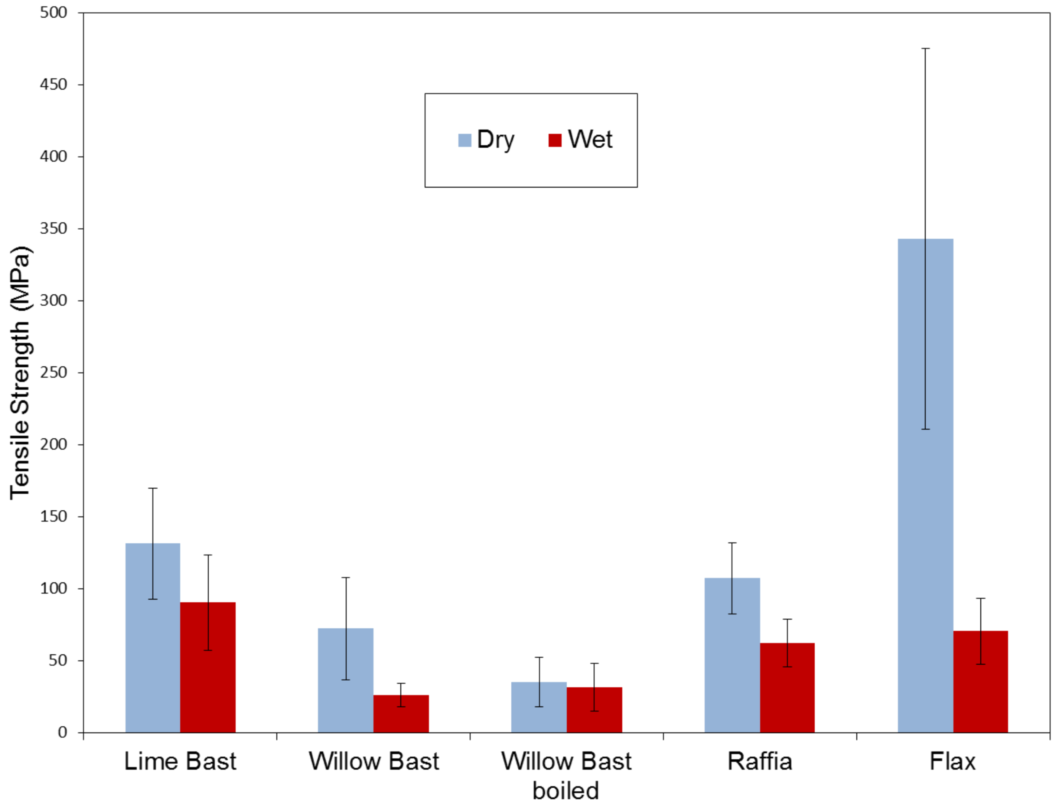

Figure 4. Comparison of the ultimate tensile strength for the different fibres tested in 'wet' and 'dry' conditions.

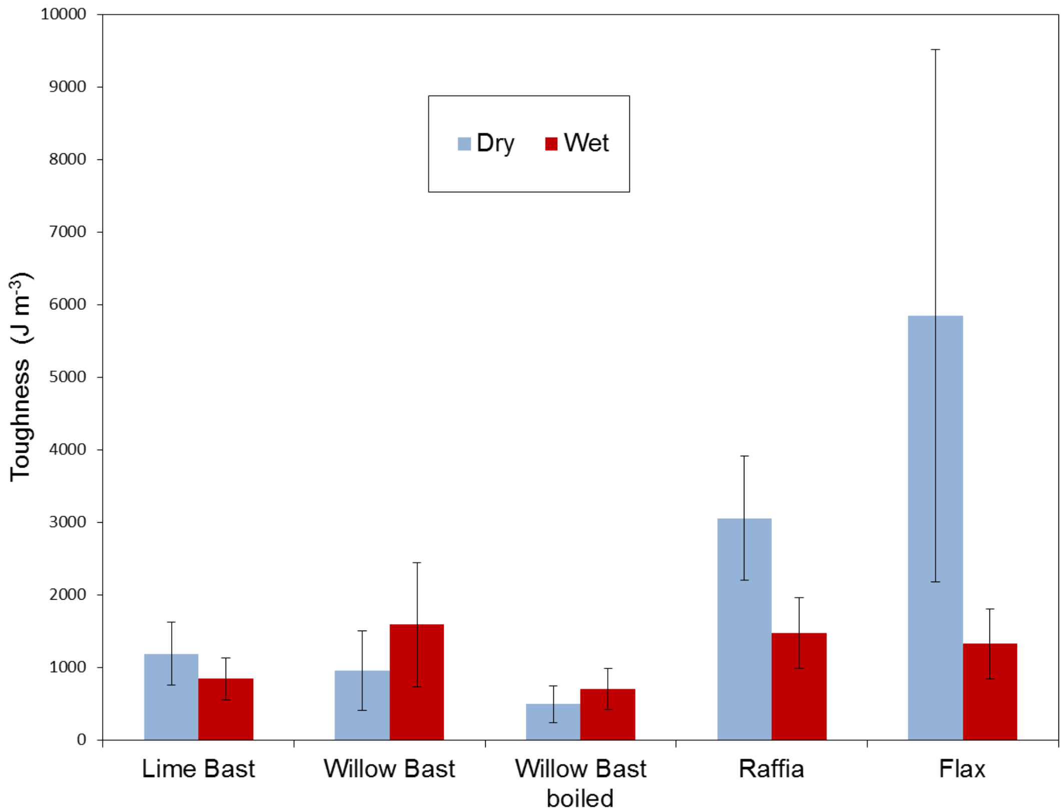

Figure 5. Comparison of the toughness for the different fibres tested in 'wet' and 'dry' conditions.

Comparison with published observations

The results for dry flax are in agreement with the mechanical properties described in the textile industry literature, where flax is described as “stronger than cotton, but it is also more brittle and less flexible” (Hencken Elsasser 2010, 52). Comparing all fibre strips by looking at the tensile strength error bars, the results show that no fibre strips were stronger when wet, indeed three (flax, willow bast, raffia) are significantly weaker. This is in contrast to the properties of flax and more generally cellulose fibre strips that are often cited in the literature as increasing in strength through wetting (Collier *et al.* 2009,83; Hencken Elsasser 2010,52; Kornreich 1952,16,fig.8). Tests on a cord of lime bast have also claimed it was stronger when wet (Troset and Aunrønning 2003 in Myking *et al.* 2005; 70). This is contrary to the results presented here and may be due to several factors. In literature sources, it is often unclear if it was individual fibres, fibre bundles or fibre strips that were being tested, or for how long the wet samples were soaked, which may affect the way they fracture. In this experiment we tested fibre strips, whereas it is typical within the textiles industry, from which most results originate, to test single fibres. The discrepancy may also be due to the way the results and errors are expressed and interpreted. For example, figures for breaking tenacity of flax standard and wet (in Collier *et al.* 2009, tab.2.4,59) are expressed as a specific strength (grams per dernier) but it is not stated if both measures are calculated on a dry basis; further, the stated ranges overlap. Thus, whereas Collier *et al.* consider the flax to be stronger when wet (Collier *et al.* 2009, 83), the conditions for which this statement holds are probably different from those applied in this study.

Across all the tests wet fibres are typically less stiff and less brittle under a given load. In practice this means fibres will be more pliable and easier to work wet than dry. These results fit with the experience of spinning these fibres which are easier to work when wet. However, the fibres are also weaker when wet, which means that they need to be handled more carefully. The brittleness of dry flax is noted elsewhere (Collier *et al.* 2009, 83) and is apparent in the results presented here. This means that dry flax will feel stiffer than either lime or willow, as flax fibres resist deformation. As the results for flax show, one of the weaknesses of flax is its brittleness which could make it difficult to spin and weave fibres, yet this can be readily overcome simply by working the fibres while damp.

On the basis of these results we return to the original question: did flax fibres provide early farmers with an especially good material that was superior to alternative fibres such as lime or willow bast? According to the results gained in this experiment, flax fibre strips wet or dry offered equally good, or in the case of dry strips, superior mechanical properties to fibre strips of lime and willow, as processed by the methods outlined in the materials section.

DISCUSSION

These results lead to two points of discussion. 1) Evaluation of the experiment and potential developments. 2) Contribution of results to understanding the materials choices people made in specific Mesolithic and Neolithic contexts.

Evaluation of the experiment

This experiment specified how the fibre strips were harvested and processed the growing season, time of harvest and processing can affect fibre properties. For example, flax fibre, when harvested green and the seed capsules are still forming, the fibres will be long and supple; harvested too early and fibres will be fine but weak; when left to over-ripen flax fibres will be brittle (Adugna 2012, 305; Médard 2005). The increased lignification of late-harvested, coarse fibres adds to their strength. The flax in this study was harvested late for seed and this may in part account for the brittleness and high tensile strength. Studies of modern flax show variations in fibre tensile strength as the genotype, soil, climate and agronomic practices influence the chemistry and structure of the cell walls affecting fibre properties (Norton et al. 2006, 15-16). In published tests on flax, the variety and season (year of harvest) were found to contribute to the fibres' strength while both fine and coarse fibres produced fibres with high tensile strength (Norton *et al* 2006, 22). Over-retting can cause loss of fibre quality (Adugna 2012, 305). In preparing lime bast for this experiment it was noted that bast closest to the wood was finer and that closest to the bark was coarser; aspects which may affect properties and require further study. It is reported that lime bast processed without retting may have double the breaking load (Myking *et al.* 2005: 70). Future tests could consider fibres retted for different lengths of time, processed by alternative methods, or from different areas of the branch or tree. In this experiment the willow fibre strips were processed by two different methods (Table 1), and the differences in mechanical properties are slight, especially when compared with the results between species. Further tests are necessary to establish if the differences between species are greater than the differences between fibre strips of the same species processed by different methods.

Due to selective breeding it remains questionable whether the modern flax fibres are similar to those used in the past, or indeed are different from the wild flax (Abbo *et al.* 2014). It seems likely that lime and willow bast would be the same as those available today. This initial project seeks to test the major differences between the fibre strips obtained from flax, lime and willow. It would be desirable to carry out further tests on fibres processed by different means and a wider range of species.

Material choices

Processed flax fibre is physically finer than tree bast and hence easier to work into fine threads (Rast-Eicher 1997, 311). In the Neolithic dwellings of the circum-alpine area for example, tree bast fibres were used for cords (1-3mm diameter) and thick cords (over 3mm diameter) and only rarely finer threads (less than 1mm diameter) and were mostly used for twined textiles (Figure 2a); in contrast flax fibre was mainly used for fine threads of less than 1mm in diameter and mostly used for woven textiles (Médard 2003, 80-83; Médard 2012, 368) (Figure 2b). That flax was more commonly used for fine threads and woven textiles suggest a relationship between the physical properties of the fibre, technology and product. Based on the mechanical tests presented here, the results for flax showed that when dry it is tougher and had a higher tensile strength than lime and both samples of willow. In terms of performance, this means that relative to cross-sectional area, the dry flax strips tested required more force to break them and were better able to absorb shocks (energy) than either the lime or willow. Flax may have been used for finer yarns because, in relation to cross-sectional area, when dry it is stronger and tougher than lime or willow tree bast. Flax fibre may have been advantageous when used in fine, woven textiles as it would produce a tougher, stronger material more able to resist tearing and breaking than tree bast. Fine textiles are time consuming to make and this may have aided their longevity.

On the basis of data obtained in this experiment, dry flax offers some superior properties to the other fibres tested. Wet, however, the mechanical properties of flax were comparable to those of lime and willow bast. On this basis, the willow bast net used by the hunter-fishers of Antrea, Russia (Burov 1998, 61) may have been only slightly less efficient than one of flax. In the Late Neolithic lake dwellings flax was the preferred material for nets (Rast-Eicher 1997,311) with nets occasionally produced tree bast, for example at Wetzikon-Robenhausen, Switzerland (Altorfer and Médard 2000, 57-8) and lime bast was used for the netting and cords used by Late Neolithic Iceman (Pfeifer and Oeggl 2000, Putzer 2011, 33-5). We may assume that Mesolithic and Neolithic people gained experience of these performance characteristics through using nets when fishing and hunting.

Of the fibrous artefacts of the Neolithic circum-alpine area, tree bast fibre artefacts were more common those of flax (Médard 2012, 368; 2010, 71-73, 107). This shows that despite of the potentially impressive mechanical properties of dry flax, in quantity tree bast fibres remained the key fibre. This may be due to several reasons. Tree bast fibres are a woodland resource, not requiring farm land and can be foraged or managed through coppicing (Harris 2014, 5). However, early farmers applied their cultivation skills to grow flax for fibre. Although Allaby *et al.* (2005) argue that flax was domesticated for its oil, once domesticated, the dual crop of fibres and oil may have been part of its appeal. As fibres are needed in large quantities for all manner of string, textiles and basketry, a range of fibres from across the landscape may have been an important strategy for materials acquisition during the Mesolithic and Neolithic.

CONCLUSION

To question why early farmers grew flax as a fibre crop from a materials perspective opens up a new and compelling direction of research. In this experiment we provide results for the mechanical properties of flax, lime bast and willow bast fibre strips processed according to the methods described; through identification of archaeological material these plant fibres are known to have been used by people in the Neolithic. The results obtained in this experiment demonstrate that under dry conditions and in comparison to lime and willow, flax has good performance characteristics as it is stronger and tougher. When wet, the mechanical properties of flax are less distinguishable from the other fibre strips tested. It seems in part that a farmer’s motivation to grow flax could have been to gain fine fibres that were superior in some aspects to those available from two indigenous fibre species: lime and willow. However, the mechanical properties must be considered along with other material properties and as just one of many material (aesthetic, fineness, sensory appeal) and technological choices (production, availability) in the decision to use a fibre. This raises important issues in the motivations for farmers to prepare land, sow, tend and harvest a flax crop. Fibres are key resources and their properties are important aspects of such a resource.

The results of this initial project show a promising line of investigation to understand the Mesolithic / Neolithic transition from a materials perspective, and the choices this engenders. In the future, it would be desirable to undertake further tests on species such as oak and poplar bast which were also used in this period. In addition, it would be relevant to increase the number of tests on samples of the same species and test fibres processed according to different methods and grown in various climatic conditions.

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