Article:
Haule, LV, Carr, CM and Rigout, M (2016) Preparation and physical properties of regenerated cellulose fibres from cotton waste garments. Journal of Cleaner Production, 112 (5). pp. 4445-4451. ISSN 0959-6526

https://doi.org/10.1016/j.jclepro.2015.08.086

As published in Journal of Cleaner Production (2015)
Available online 29 August 2015
doi:10.1016/j.jclepro.2015.08.086

Preparation and physical properties of regenerated cellulose fibres from cotton waste garments

L. V. Haule * · C. M. Carr [1] · M. Rigout [1]

ARTICLE INFO

Article history:
Received 20 February 2015
Received in revised form
18 August 2015
Accepted 19 August 2015

Keywords:
Recycling
Regenerated fibres
Lyocell
Waste cotton garments

ABSTRACT

The aim of this research was to investigate the recycling of cotton waste garments by fibre regeneration. Easy care finished cotton fabrics and indigo dyed waste denim garments were successfully purified, dissolved in a suitable solvent and spun into fibres. The physical properties of the resultant fibres were compared with standard lyocell fibres spun from wood pulp and the fibres regenerated from the cotton waste garments exhibited improved mechanical and molecular properties relative to the typical fibres regenerated from wood pulp. Furthermore the results have indicated that a suitable blend of wood pulp and pulp reclaimed form cotton based waste garments can produce fibres with properties that are intermediate to cotton and lyocell fibres. The results suggest an alternative approach to fibre resource management by converting cotton based waste garment through regeneration processing into second lifetime cellulosic fibre. The approach will contribute to the reduction of both economic and environmental impact of waste garments and better management of resources required for production of cotton and synthetic fibres.

1. Introduction

The increasing number of fashion seasons in the retail market has led to shorter and shorter "lifetimes" for textiles garments and an increase in discarded clothing associated with the changing fashion. Accordingly the percent contribution of textiles within municipal waste is increasing (DEFRA, 2006 and DEFRA, 2009) and leading to an increase in land fill tax (Ali and Courtenay, 2014). Therefore there is need for exploring alternative solutions that are more sustainable and lessen the environmental impact of waste textiles. Some of the alternatives for the recycling of cotton waste garments involve conversion of the cotton based waste garments by various methods into alternative renewable energy resources (Hong et al., 2012, Shen et al., 2013, Jeihanipour et al., 2010 and Jeihanipour and Taherzadeh, 2009). While the approach of converting waste garments into renewable energy resources helps in reducing the environmental impact of waste garments unfortunately there is no reduction in the pressure on water and land requirements for the production of cotton and synthetic fibres.

The most common avenue of extending the usage of textiles garments is through the export of second-hand clothing to Africa (DEFRA, 2006 and DEFRA, 2009; Hawley, 2006a and Hawley, 2006b; Baden and Barber, 2005). However the literature and economic logic suggest that this "recycling route" adversely affects the local textile manufacturing industry in Africa (Amankwah-Amoah, 2015, Hawley, 2006a and Hawley, 2006b; Baden and Barber, 2005) and again is encouraging in developing alternative approaches. Traditional mechanical recycling converts the waste garments by pulling the fabric into yarns and fibres and then reconstituting back into either recycled yarns for textile applications or into other applications such as nonwoven products, carpet underlay, sound insulators, thermal insulators, phase change materials, geo-textile materials, odour removal material, filtration material, and many others (DEFRA, 2009). However the mechanical recycling can only produce yarn with limited tex due to yarn breakage during spinning process (Lebedev, 1995) and wider tex ranges could only be achieved by blending with virgin cotton fibres (Merati and Okamura, 2004). Some of standards and specification for technical applications such as geo-textile prohibits the use of mechanically recycled yarns regardless of its physical performance (DEFRA, 2009). It is therefore obvious that the quality of the mechanically recycled textile material cannot be the same as that of the first life cycle of the same material, hence there is need to promote recycling by chemical conversion of the waste garments into fibres for the second life cycle. The chemical conversion of the waste garments into new fibres must consider the separation of fibre blends and removal of finishes such as dyes and other functional finishes which may hinder the conversion process.

In order to overcome the environmental and economic impact of the waste textiles, a closed loop recycling technology is now being considered. The first attempt to recycle cotton based waste garments by regeneration into fibres was patented by Firgo et al. (1997) where the process involved dissolution of the waste garments in N-methylmorpholine N-oxide (NMMO) solution, spinning and regeneration of the cellulose fibres. The physical properties of the fibres were relatively higher than the other regenerated and cotton fibres. However in the Firgo et al. patent, no consideration was taken for the effects of finishes such as dyes and easy care finishes on the dissolution of the waste garments. Subsequently Haule et al. have demonstrated that a typical easy care finish applied to cotton garments is durable almost through the entire first life cycle of the garment (Haule

* Corresponding author. Present address: College of Engineering and Technology, University of Dar es Salaam, Dar es Salaam, Tanzania.
E-mail address: liberato.haule@udsm.ac.tz (L.V. Haule).
[1] Present address: School of Design, University of Leeds, Leeds LS2 9JT, UK.

As published in Journal of Cleaner Production (2015)
Available online 29 August 2015
doi:10.1016/j.jclepro.2015.08.086

et al., 2012). Further work demonstrated that the easy care finish could also dramatically reduce the NMMO solubility of the cotton waste garments during fibre making process and the methods for removal of the easy care finishes were optimized in order to establish viable commercial processing technology (Haule et al., 2014). Therefore this work extends the previous work by studying the dissolution of the purified cotton waste garments in NMMO solution and subsequent spinning into new fibres.

The choice of NMMO solution as a solvent for the waste cotton garments is due to the fact that the solvent can dissolve completely cellulose without any degradation, is 99% recyclable, safe to work with and safe in the environment in case of any spillages (Woodings, 1995). The dissolution of cellulose in NMMO solution is achieved by constant mixing at increasing temperature and reduced pressure so as to dehydrate the tertiary mixture of NMMO, water and cellulose into cellulose-NMMO solution (Chanzy, 1982, Chanzy et al., 1990 and Kim et al., 2005). The dehydrated cellulose/NMMO solution is formed in a spinneret, stretched in an air gap and then the cellulose fibre is precipitated in any polar liquid which is a non-solvent to the cellulose (Johnson, 1969 and Firgo et al., 1997). During the dissolution process care should be taken to ensure no oxidation of the solvent occurs, in this case antioxidants are incorporated in the dissolution process. The process of dissolution of cellulose in NMMO solution and regeneration of fibres is known commercially as a lyocell process and the resultant fibres are generically known as lyocell fibres. The lyocell fibres are characterized by a high degree of orientation of the fibrils and weak intrafibrillar hydrogen bonds resulting in the fibres being susceptible to fibrillation under mechanical action and wet conditions (Huong Mai et al., 2008, Zhang et al., 2005 and Taylor, 1998). Although this tendency to wet fibrillation can make dyeing of lyocell fibres more difficult, if controlled, fibrillation can introduce an attractive appearance and appealing handle to garments made from the lyocell fibres (Bates et al., 2004, Bates et al., 2008, Goswami et al., 2007, Zhang et al., 2005 and Taylor, 1998). Additional beneficial features of the lyocell fibres are the relatively high elasticity and regain that provide shapeability and comfort to the garments. Overall the lyocell process is considered as an environmentally benign process and the lyocell fibres have attractive mechanical and comfort properties.

Therefore in this paper the lyocell process was considered for the regeneration of fibres from the 100% cotton waste garments from various sources. The cotton based waste garments were purified, dissolved and spun into fibres. The resultant properties of the recycled fibres such as molecular weight, density, tensile and Dynamic Mechanical Analysis (DMA) were determined and discussed with respect to the standard lyocell fibres.

2. Material and methods

2.1. Methods

2.1.1. Preparation and purification of the fabrics

In order to simulate the effect of extended washing during domestic usage a 100% plain woven cotton fabric, 152 g/m2, was washed 50 times with ECE-phosphate based detergent in a Wascator FOM-71 machine, as previously reported (Haule et al., 2012), and the fabric was the source material for deconstruction into pulp and spinning of regenerated lyocell, ReCell-1 fibres. Similarly in order to prepare crosslinked crease resistant fabrics the plain woven cotton fabric was treated with 100 g/L DMDHEU easy care finish (Haule et al., 2012). The easy care finished cotton fabric was then Wascator washed 50 times with ECE-phosphate based detergent and subsequently purified in acid-alkali solution to produce a component source of the ReCell-2 fibres (Haule et al., 2014). The ReCell-2 fibres were prepared from a blend of 20% cellulose recovered after purification of the DMDHEU treated cotton fabrics and 80% wood pulp. In order to prepare the waste indigo dyed denim garments for deconstruction into pulp for spinning, 5 pairs of indigo dyed waste denim were washed once with ECE-phosphate based detergent, tumble dried, zippers, buttons and threads removed manually and considered the source of ReCell-Denim fibres.

2.1.2. Deconstruction of the fabrics

The purified cotton fabrics were deconstructed into a pulp using a laboratory Valley beater (Weverk 45486) with the fabrics/garments hand-cut into 10 × 10 mm pieces prior to introduction into the beater deconstruction process. The parameters used in the beating process were set in accordance with the Technical Association of Pulp and Paper Institutes (TAPPI) standards (TAPPI, 1996). 360 g of fabric pieces was mixed in 23 L of water to obtain a consistency of 1.56%. The gap between beater roll and beater plate was adjusted by putting a standard weight of 4.5 kg on the beater plate lever arm. After running the Valley beater for 90 min, the stock was collected, drained and air dried for further tests.

2.1.3. Determination of the molecular properties of the prepared pulp

The limiting viscosity of the pulps prepared from various types of material was determined as per the previously reported method (Haule et al., 2012). The viscosity average molecular weight (Mv) of the fibres was calculated by determining the limiting viscosity and using the Mark–Houwink relationship (Immergut and Eirich, 1953), Equation (1).

$$[\eta]=Km(Mv)^{a} \quad (1)$$

where Km and a are constants and for the CED solution are 1.33 and 0.9, respectively, and [η] is the limiting viscosity of the cellulose.

2.1.4. Dissolution and spinning of fibres

In order to spin fibres the required spinning dope was prepared by mixing 300 g of 50% NMMO solution with 27 g pulp and 0.2 g n-propyl gallate using a laboratory scale mixer. The dissolution process was made possible by mixing the pulp and NMMO solution at increasing temperature and vacuum at suitable steps until the final spinning dope was composed of 9% cellulose, 13% water and 78% NMMO. For every sample the dissolution dope was checked for fibre solubility using a light microscope. The fibres were then spun from a laboratory scale spinning machine at Lenzing AG, Austria. The spinneret used had 19 holes of 100 μm in size and the spinning temperature was 115 °C. The dope throughput was 0.03 g/min

As published in Journal of Cleaner Production (2015)
Available online 29 August 2015
doi:10.1016/j.jclepro.2015.08.086

per hole, the air gap conditions were set at 30 mm, 24 °C and 53% relative humidity.

The winding speed was 25.1 m/min. and water was used to precipitate the fibres. The fibres were then oven dried at 60 °C overnight.

2.1.5. Determination of linear density

The fibre linear density (L, in dtex) was calculated from the relationship between the winding speed (Ws, in m/min), percent cellulose in the spinning dope (cel) and the rate of extrusion of the dope (Ds, in g/min) as per Equation (2):

$$L = 121 \times \frac{D_s}{W_s} \times \text{cel} \tag{2}$$

2.1.6. Determination of fibre specific gravity

The density of the fibres was determined using a microbalance (Metter Toledo density balance) with an accuracy of ±0.0001 g/cm3 and the liquid used was xylene (density 0.865 g/cm3 at 20 °C). The fibres were first weighed in air and then weighed in the xylene liquid. The weight of the fibres in air (A) and in liquid (B) and the temperature of the immersion liquid were recorded. The density of the immersion liquid at the recorded temperature was determined using Equation (3):

$$\rho_t = \frac{\rho_0}{\beta(T_f - 20) + 1} \tag{3}$$

where ρ_t and ρ_o are the densities of the xylene liquid during the test and at 20 °C temperature, respectively, β is the volumetric temperature coefficient of xylene liquid (0.00086v/v°C), Tf is the temperature of the xylene liquid during sample testing and then the density of the fibres (ρ) was calculated as:

$$\rho = \frac{A}{(A - B)(\rho_t - \rho_z)} + \rho_2 \tag{4}$$

where ρ2 is the density of air (0.0012 g/cm^3).

Ten replicates were measured and the mean was recorded.

2.1.7. Determination of tensile properties of the fibres

The tensile properties of the fibres were determined using an Instron tester Series IX machine with the tested specimens either pre-conditioned at 65% relative humidity and 23 °C for 24 h or for the wet fibres pre-soaked in water for 2 h (British Standards, 1978). The testing was carried out in a room conditioned at 65% relative humidity and 23 °C. The test methods for the fibres were in accordance to the British standards (British Standards, 1978) and a pre-tensioning of 0.5 cN/tex and crosshead speed of 10 mm/min were applied to the fibres. For more effective analysis the ends of the fibres specimens were glued to cardboard frames with epoxy resin (Chae et al., 2002) and then clamped in the Instron jaws. From the acquired data the mean tensile strength and elongation at break were reported.

2.1.8. Determination of dynamic mechanical analysis (DMA) properties

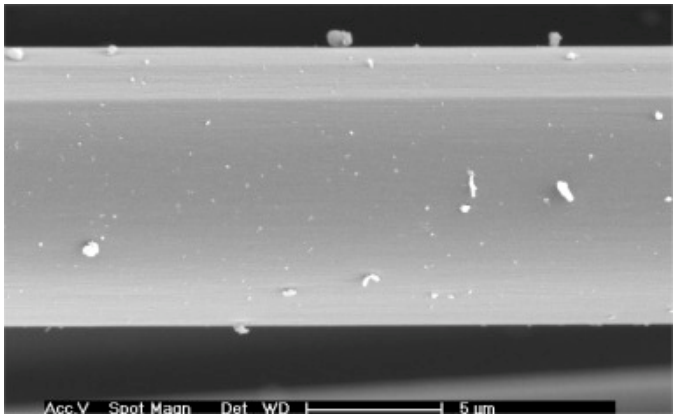

Fig. 1. SEM micrograph of Lyocell fibres at 5000_ magnification and an accelerating voltage of 5 kV.

The variation in the mechanical properties of the fibres with temperature was assessed by a DMA Q800 V7.5 instrument with the clamp mode in tension for film and fibres. In order to ensure firm clamping and minimum deformation of the specimen, the ends of the fibres specimens were glued to cardboard frames with epoxy resin and then introduced into the machine jaws (Chae et al., 2002). The analysis range was set with a standard temperature ramp programme, with heating of 3.00 °C/min from 25 °C to 200 °C and testing carried out at constant static strain and a frequency of 1 Hz.

2.1.9. Scanning electron microscopic (SEM) analysis

The surface morphology of the fibres was investigated using a Hitachi EDAX-S300N SEM instrument. The fibres were pre-gold coated using a SEM E5100 system (Polaron Limited) which was operated at 0.01 torr with current of 20.0 mA for 3 min. For all SEM imaging the secondary electron (SE) detector and a 5 kV accelerating voltage was used.

3. Results and discussion

3.1. Surface morphology of the fibres by SEM

The SEM micrographs for lyocell, ReCell-1, ReCell-Denim and ReCell-2 fibres, Fig. 1-4, indicated the surface of

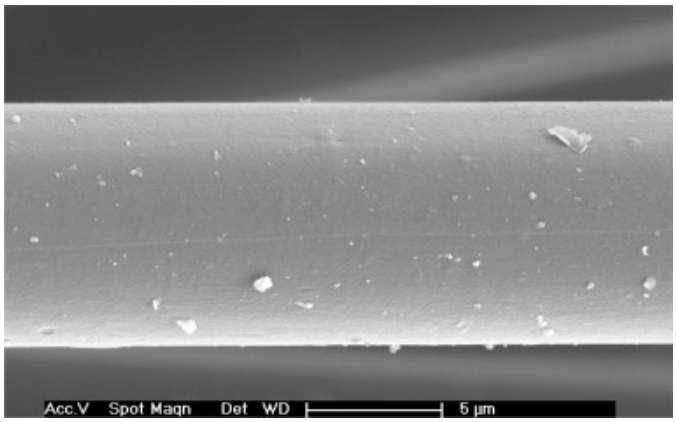

Fig. 2. SEM micrograph of ReCell-Denim fibres at 5000_ magnification and an accelerating voltage of 5 kV.

As published in Journal of Cleaner Production (2015)
Available online 29 August 2015
doi:10.1016/j.jclepro.2015.08.086

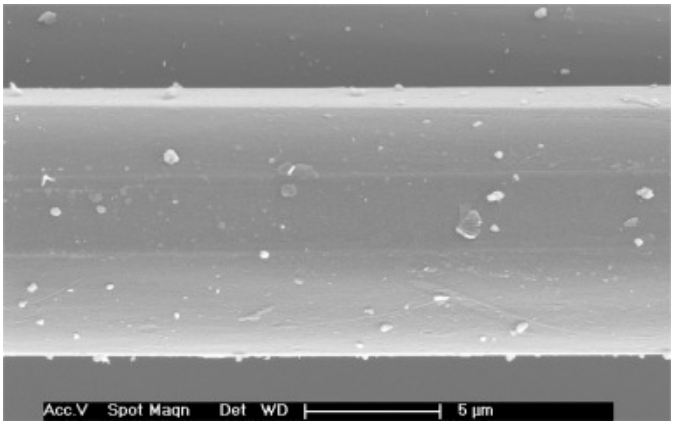

Fig. 3. SEM micrograph of ReCell-2 fibres at 5000_ magnification and an accelerating voltage of 5 kV.

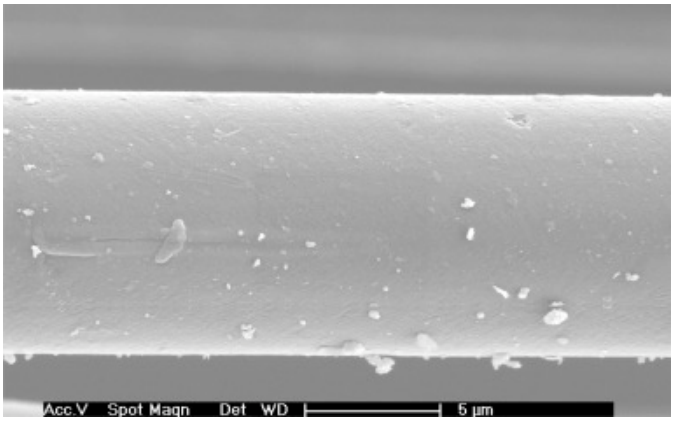

Fig. 4. SEM micrograph of ReCell-1 fibres at 5000_ magnification and an accelerating voltage of 5 kV.

all the studied fibres appeared to be smooth, with no surface fibrillar structure observed. However surface artefacts/contaminants were evident in the micrographs and could arise due to fibre handling or general processing.

3.2. Molecular properties of the fibres

Examination of the molecular properties of the fibres as determined by viscometry indicated that the fibres regenerated from cotton fabrics/garments have a higher molecular weight than the standard lyocell fibres, Table 1. The average molecular masses of the ReCell-1, ReCell-Denim and ReCell-2 fibres were 116%, 12% and 4%, respectively, higher than the molecular mass of lyocell fibres. The higher molecular masses of the ReCell fibres were due to the difference in the corresponding molecular properties between the wood pulp and the pulp reclaimed from multiple washed cotton waste garments as previously reported (Haule et al., 2014).

Table 1
Molecular weight and density of ReCell and Lyocell fibres.

Fibre type	Viscosity – average molecular weight (Mv) [g/mol]	Density (g/cm^3)
Lyocell	494	1.51 ± 0.01
ReCell-1	1066	1.51 ± 0.01
ReCell-Denim	623	1.51 ± 0.01
ReCell-2 (blend of 80% wood pulp and 20% reclaimed cotton pulp)	517	1.51 ± 0.01

The low molecular mass of the ReCell-Denim fibres relative to the lyocell fibres was probably due to higher degradation of the denim during its wash/wear lifetime when compared to the ReCell-1 fibres which were produced from white cotton fabric that has only experienced extended laundering over 50 cycles. The densities of all the regenerated fibres were similar.

In developing a commercial approach to the fibre processing, blending of wood pulp and reclaimed cotton pulp (ReCell-2) was evaluated and found to deliver an improvement in the molecular properties of the resultant fibres to a level which is intermediate to that of lyocell and the ReCell-1 fibres. For instance, a blend of 20% cotton reclaimed pulp and 80% wood pulp could increase the overall molecular mass of the fibres by 4% with respect to the standard lyocell, Table 1 This would suggest that the pulp reclaimed from waste cotton garments can be used to regenerate fibres with properties similar to the fibres spun from 100% wood pulp. Furthermore the blend between waste cotton and wood pulp could result in fibres with similar properties.

3.3. Mechanical properties of the fibres

Comparison of the mechanical properties of the fibres regenerated from cotton-based waste garments and lyocell fibres, Table 2, indicated that the cotton waste garments can be regenerated into ReCell fibres with a linear density almost equal to that of the lyocell fibres. A feature of the ReCell-2 fibres was the lower coefficient of variation in the linear density which may be due to improved rheology of the blend pulp which formed into fibres relatively easily, Table 2.

Examination of the dry tenacity of the fibres, Table 2, as measured at conditioned state of 23 °C and relative humidity of 65% indicated that the tenacity was decreasing in the order of:
Recell-1>ReCell-Denim>ReCell-2>lyocell

The ReCell-1 and ReCell-Denim fibres had tenacity values which were 40% and 22%, respectively, higher than the tenacity for lyocell fibres. A blend of 20% cotton pulp and 80% wood pulp improved the tenacity of the resultant fibres (ReCell-2) by 7% with respect to lyocell fibres. The elongation at break of the conditioned fibres decreased in the order of lyocell > ReCell-2 > ReCell-Denim > ReCell-1. The ReCell-1 and ReCell-Denim had elongation at break which is 18% and 13%, respectively, less than the lyocell fibres. Corresponding ReCell-2 fibres has an elongation at break of 12% less than the lyocell fibres. This indicated that blending of wood pulp and reclaimed cotton pulp could produce fibres with higher tenacity and lower elongation at break than lyocell fibres. The variation in tenacity and extension at break among the fibres under investigation could be due to the differences in their molecular properties.

Examination of the dry modulus of the fibres indicated that the fibres modulus decreased in the order of ReCell-1 > ReCell-Denim > ReCell-2 > lyocell, Table 2. The ReCell-1, ReCell-Denim and ReCell-2 fibres moduli were 48%, 45% and 2%, respectively, higher than the modulus for lyocell fibres. Similarly examination of the stress/strain curves for both ReCell and lyocell fibres indicated that the ReCell fibres have higher tenacity and modulus but lower extension at

As published in Journal of Cleaner Production (2015)
Available online 29 August 2015
doi:10.1016/j.jclepro.2015.08.086

Table 2
Tensile properties of Lyocell and ReCell fibres.

Fibre tensile properties	Lyocell		ReCell-1		ReCell-Denim		ReCell-2	
	Mean	CV	Mean	CV	Mean	CV	Mean	CV
Linear density (dtex)	1.3	9.4	1.3	8.8	1.3	9.1	1.3	4.3
Dry tenacity (cN/tex)	34.7	9.6	48.7	10.1	42.5	8.4	37.2	10.4
Wet tenacity (cN/tex)	28.8	8.8	42.4	14.6	35.2	12.5	32.6	8.1
Dry elongation (%)	11.2	14.1	9.2	14.1	9.7	13.4	9.9	17.1
Wet elongation (%)	13.2	14.0	11.0	13.6	14.2	18.6	14.1	17.1
Dry modulus (cN/tex)	205	144	303	109	298	85	210	71
Wet modulus (cN/tex)	112	89	152	56.0	162	90	116	55

Cv = coefficient of variation

break than the lyocell fibres, Fig.5. This higher tenacity and modulus could be due to the differences in the properties of the initial reclaimed cotton and the virgin wood pulps and the rheology properties of their respective spinning dopes. The limiting viscosity, hence the degree of polymerization of the cellulose has been identified an important parameter for the quality of spinning of fibres (Braverman et al., 1990 and Fink et al., 2001). The reclaimed cotton pulp had a higher DPv which gave a better molar mass distribution of the cellulose during dissolution and spinning of fibres than wood pulp. This resulted in high molecular weight fibres and better structure formation of the cotton reclaimed pulp than the wood pulp. The higher tenacity and modulus of the ReCell fibres was mainly due to the higher molecular weight as indicated in Table 1.

A common feature of the mechanical properties of all the tested fibres was the unusual variability levels in the coefficient of variation, Table 2, and this was possibly due to the methodology used to mount the fibres for the tensile tests. Further work is underway to improve this aspect of the fibre analysis.

Re-examination of the wet properties of the ReCell and lyocell fibres indicated that both fibres experienced a reduction in tenacity and modulus and an increase in elongation at break when in the wet state, Table 2. The two types of fibres have almost the same level of reduction in the wet tenacity and modulus. In particular the wet tenacity of the ReCell-1, ReCell-Denim and ReCell-2 fibres decreased by 13%, 17% and 12%, respectively, whereas the corresponding properties for lyocell fibres decreased by 17%. In addition the wet modulus of the ReCell-1, ReCell-Denim, ReCell-2 and lyocell fibres decreased by 50%, 46%, 45% and 45%, respectively. The elongation at break of the wet ReCell-1, and lyocell fibres was reduced by 20% and 18%, respectively, whereas that of ReCell-Denim, ReCell-2 fibres decreased by 46% and 42%, respectively. The deterioration of mechanical properties of the regenerated fibres in the wet swollen state was due to the weakening of the cellulosic inter-polymer chain hydrogen bonding fibres in water. When cellulose fibres are swollen in water, the polar water interacts with the hydroxyl groups of the amorphous faction of the cellulose, which disrupt the inter-hydrogen bonding in the cellulose hence reducing the fibres ability to bear loads and increases the elongation at break of the fibres. The nature of the relatively high reduction in elongation at break of the wet ReCell-Denim and ReCell-2 fibres is uncertain at present but is probably a reflection of the greater cellulosic modification during their “first lifetime” experience.

A comparison of tensile properties of the ReCell, lyocell and cotton (Cook, 1984, Bredereck and Hermanutz, 2005, Woodings, 1995 and Taylor, 1998) fibres indicated that the tenacity of the ReCell fibres was above that of cotton and standard lyocell, however the extension for ReCell fibres was intermediate between the cotton and lyocell values, Fig. 6. The observed extensibility performance of the ReCell fibres

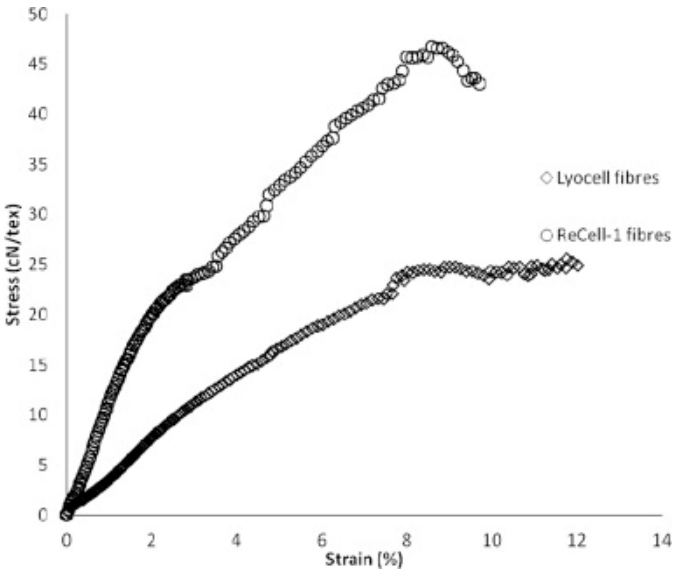

Fig. 5. Stress/strain curves for>-Lyocell and B-ReCell-1 fibres (each 1.33 dtex).

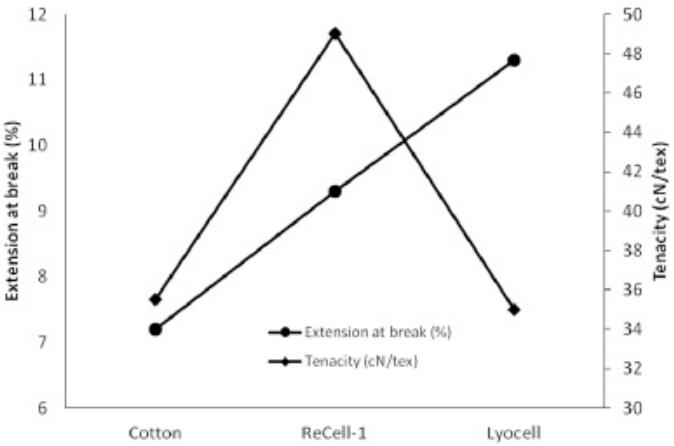

Fig. 6. Comparison of extension at break (C) and tenacity (A) of ReCell, Lyocell and cotton fibres. The cotton figure values are literature-based (Cook, 1984; Bredereck and Hermanutz, 2005; Woodings, 1995; Taylor, 1998).

As published in Journal of Cleaner Production (2015)
Available online 29 August 2015
doi:10.1016/j.jclepro.2015.08.086

perhaps provides an opportunity in garment making where the intermediate performance offers advantages over both cotton and lyocell. The relatively higher tenacity of the ReCell fibres compared to the virgin cotton tenacity was probably due to the fact that during purification and dissolution of the cotton waste garments, the "degraded and modified" oligomers and polymers also dissolve into the precursor cellulosic dope but during subsequent spinning of the dope into fibres these weakened cellulose molecules were not reconstituted into the cellulosic fibres. Hence the fibres are relatively free from polymeric "defects" and offer the ability to bear higher tensile loads.

3.4. DMA analysis of the fibres

The DMA technique was used to assess the effect of temperature on the mechanical properties of the ReCell-1, ReCell-2 and ReCell-Denim fibres and their properties compared with the standard lyocell fibres. The specimen was heated at constant rate of 20–200 °C and during the heating the specimen was deformed at constant strain under a frequency of 1 Hz.

A comparison of storage modulus of the fibres at increasing temperature indicated that the fibres reclaimed from cotton waste garments have higher storage modulus that the lyocell fibres, however they all showed a similar rate of change of storage modulus with temperature especially in the temperature ranging from 20°C to 140°C, Fig. 7.

The higher storage modulus for the fibres regenerated from waste cotton garments was related to its relatively higher degree of polymerization. The similarity in the slopes of the storage moduli–temperature curves for the ReCell fibres and lyocell fibres was mainly due to the similarity in their dissolution and physical spinning conditions

Therefore it can be concluded that the DMA results highlighted the similar behaviour between the ReCell fibres derived from cotton waste garments and the standard lyocell fibres in terms of the response of the mechanical properties of the fibres to deformation at increasing temperature. Hence it appears the new ReCell fibres can withstand processing conditions similar to those of lyocell fibres.

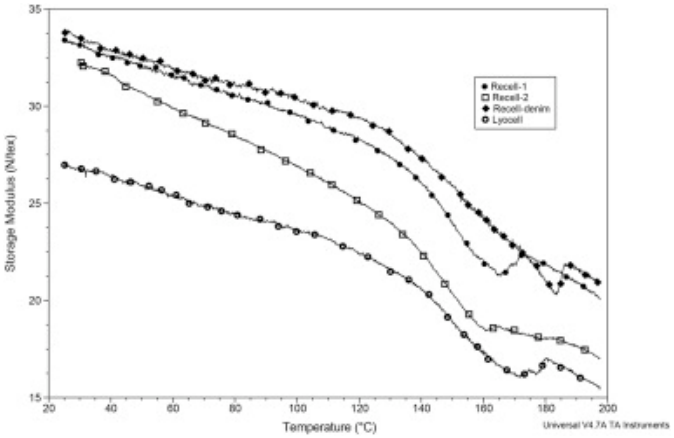

Fig. 7. Storage modulus of A-ReCell-Denim, C-ReCell-1, -ReCell-2 and B-Lyocell fibres with increasing temperature.

4. Conclusions

The pulps prepared from a range of typical "used" cotton fabrics were successfully dissolved in NMMO solution and spun into fibres. The molecular and mechanical properties of the fibres were determined and compared to the standard lyocell fibres. Their molecular properties indicated that, the fibres spun from cotton waste garments have higher molecular weight and specific gravity than standard lyocell fibres. Furthermore results indicated that the ReCell type fibres have higher tensile properties and exhibited better wet strength recovery than the comparable lyocell fibres.

DMA studies indicated the storage modulus of the regenerated fibres decreased with temperature. The ReCell type fibres exhibited relatively higher initial storage moduli than the lyocell fibres due to the higher molecular weight of the precursor pulp material.

It is clear from this preliminary study that the waste cotton fabrics stripped of the easy care finish and indigo dyed waste denim can be regenerated into fibres with mechanical, thermal–mechanical and surface properties similar to the lyocell fibres. Furthermore the results indicate that the pulp reclaimed from cotton based waste garments can be blended with wood pulp to make fibres with properties similar to lyocell.

The overall aim of this paper was to develop a recycling technology that will reduce the increasing environmental impact of waste cotton garments. Currently the garment lifetime is extended by recycling and exporting as second hand clothing for reuse in developing countries. However this current "export for reuse option" is not sustainable due to the recognized negative impacts of the second hand clothing at the destination countries. Coupled to the export of second hand clothing is the more fundamental challenge of production of cotton and synthetic fibres and better utilization of dwindling land and water resources. Therefore this paper proposes an alternative approach to fibre resource management and the development of technology to convert cotton-based waste garments through regeneration processing into second lifetime cellulosic fibres.

Future work will focus on the characterization of fibres regenerated from waste cottons in order to provide information on the structure/properties of the fibres and their associated processing performance.

Acknowledgements

We gratefully recognise the financial sponsorship from the Tanzanian Gatsby Trust and the technical support of Lenzing, Austria, in furthering these research studies.

References

Ali, M., Courtenay, P., 2014. Evaluating the progress of the UK's material recycling facilities: a mini review. Waste Manag. Res. 32 (12), 1149e1157. http://dx.doi.org/10.1177/0734242x14554645.

Amankwah-Amoah, J., 2015. Explaining declining industries in developing countries: the case of textiles and apparel in Ghana. Compet. Change 19 (1), 19e35. http://dx.doi.org/10.1177/1024529414563004.

Baden, S., Barber, C., 2005. The Impact of Second-hand Clothing Trade on Developing Countries, Oxfam, Oxford. http://policypractice.oxfam.org.uk/publications/the-impact-ofthe-secondhand-clothing-trade-ondevelopingcountries-112464 (accessed 04.06.14.).

Bates, I., Maudru, E., Phillips, D.A.S., Renfrew, A.H.M., Su, Y., Xu, J., 2004. Crosslinking agents for the protection of lyocell against fibrillation: synthesis, application and technical assessment of 2,4-diacrylamidobenzenesulphonic

As published in Journal of Cleaner Production (2015)
Available online 29 August 2015
doi:10.1016/j.jclepro.2015.08.086

acid. Color. Technol. 120 (6), 293e300.
Bates, I., Ibbett, R., Reisel, R., Renfrew, A.H.M., 2008. Protection of lyocell fibres against fibrillation; influence of dyeing with bis-monochloro-s-triazinyl reactive dyes. Color. Technol. 124 (4), 254e258.
Braverman, L.P., Romanov, V.V., Lunina, O.B., Belasheva, T.P., Finger, G.G., 1990. Rheological properties of concentrated cellulose solutions in N-methylmorpholine-N-oxide. Fibre Chem. 22 (6), 397e400. http://dx.doi.org/10.1007/bf00632892.
Bredereck, K., Hermanutz, F., 2005. Man-made cellulosics. Rev. Prog. Color. Relat. Top. 35 (1), 59e75.
British Standards, 1978. The Determination of Tensile Elastic Recovery of Single Fibres and Filaments (Constant-Rate-of-Extension Machines) (BS 4029:1978).
Chae, D.W., Chae, H.G., Kim, B.C., Oh, Y.S., Jo, S.M., Lee, W.S., 2002. Physical properties of lyocell fibers spun from isotropic cellulose dope in NMMO monohydrate. Text. Res. J. 72 (4), 335e340. http://dx.doi.org/10.1177/004051750207200410.
Chanzy, H., 1982. Celluloseeamine oxide systems. Carbohydr. Polym. 2, 229e231.
Chanzy, H., Paillet, M., Hag_ege, R., 1990. Spinning of cellulose from N-methyl morpholine N-oxide in the presence of additives. Polymer 31 (3), 400e405.
Cook, J.G., 1984. Handbook of Textile Fibres: II. Man-Made Fibres, fifth ed. Merrow Publishing Co. Ltd, Durham.
DEFRA, 2006. Recycling of Low Grade ClothingWaste. Department for Environment, Food and Rural Affairs, London. http://www.oakdenehollins.co.uk/pdf/Recycle-Low-Grade-Clothing.pdf (accessed 04.06.14.).
DEFRA, 2009. Maximising Reuse and Recycling of UK Clothing and Textiles. The Department for Environment, Food and Rural Affairs-UK, London. http://randd.defra.gov.uk/Document.aspx?Document¼EV0421_8745_FRP.pdf (accessed 20.10.13.).
Fink, H.P., Weigel, P., Purz, H.J., Ganster, J., 2001. Structure formation of regenerated cellulose materials from NMMO-solutions. Prog. Polym. Sci. 26 (9), 1473e1524.
Firgo, H., Eichinger, D., Eibl. M., February 11, 1997. Process for the Production of a Cellulose Moulded Body. U.S Patent 5,601,767.
Goswami, P., Blackburn, R.S., Taylor, J., Westland, S., White, P., 2007. Dyeing behaviour of lyocell fabric: effect of fibrillation. Color. Technol. 123 (6), 387e393.
Haule, L.V., Rigout, M., Carr, C.M., Jones, C.C., 2012. Surface and bulk chemical analysis of the durability of an easy care finish on cotton. Cellulose 19 (3), 1023e1030. http://dx.doi.org/10.1007/s10570-012-9672-x.
Haule, L.V., Carr, C.M., Rigout, M., 2014. Investigation into the removal of an easycare crosslinking agent from cotton and the subsequent regeneration of lyocell-type fibres. Cellulose 21 (3), 2147e2156. http://dx.doi.org/10.1007/s10570-014-0225-3.
Hawley, J.M., 2006a. Digging for diamonds: a conceptual framework for understanding reclaimed textile products. Cloth. Text. Res. J. 24 (3), 262e275. http://dx.doi.org/10.1177/0887302x06294626.
Hawley, J.M., 2006b. Textile recycling: a system perspective. In: Wang, Y. (Ed.), Recycling in Textiles. Woodhead Publishing Limited, Cambridge, pp. 7e13.
Hong, F., Guo, X., Zhang, S., Han, S.-F., Yang, G., J€Onsson, L.J., 2012. Bacterial cellulose production from cotton-based waste textiles: enzymatic saccharification enhanced by ionic liquid pretreatment. Bioresour. Technol. 104 (0), 503e508. http://dx.doi.org/10.1016/j.biortech.2011.11.028.
HuongMai, B., Anelise, E., Thomas, B., 2008. Pilling in man-made cellulosic fabrics, part 1: assessment of pilling formation methods. J. Appl. Polym. Sci. 110 (1), 531e538.
Immergut, E.H., Eirich, F.R., 1953. Intrinsic viscosities and molecular weights of cellulose and cellulose derivatives. Ind. Eng. Chem. 45 (11), 2500e2511. http://dx.doi.org/10.1021/ie50527a039.
Jeihanipour, A., Taherzadeh, M.J., 2009. Ethanol production from cotton-based waste textiles. Bioresour. Technol. 100 (2), 1007e1010. http://dx.doi.org/10.1016/j.biortech.2008.07.020.
Jeihanipour, A., Karimi, K., Niklasson, C., Taherzadeh, M.J., 2010. A novel process for ethanol or biogas production fromcellulose in blended-fiberswaste textiles.Waste Manag. 30 (12), 2504e2509. http://dx.doi.org/10.1016/j.wasman.2010.06.026.
Johnson, D.L., 1969. Compounds Dissolved in Cyclic Amine Oxides. United States/Rochester Patent 3,447,939.
Kim, D.B., Pak, J.J., Jo, S.M., Lee, W.S., 2005. Dry jet-wet spinning of cellulose/N-methylmorpholine N-oxide hydrate solutions and physical properties of lyocell fibers. Text. Res. J. 75 (4), 331e341. http://dx.doi.org/10.1177/0040517505054852.
Laboratory Beating of Pulp (Valley Beater Methods):T200sp-96, 1996. TAPPI (accessed 2010.).
Lebedev, N.A., 1995. Use of natural and chemical fibre wastes in production of mixed yarns (a review). Fibre Chem. 27 (1), 52e54.
Merati, A.A., Okamura, M., 2004. Producing medium count yarns from recycled fibers with friction spinning. Text. Res. J. 74 (7), 640e645. http://dx.doi.org/10.1177/004051750407400715.
Shen, F., Xiao, W., Lin, L., Yang, G., Zhang, Y., Deng, S., 2013. Enzymatic saccharification coupling with polyester recovery from cotton-based waste textiles by phosphoric acid pretreatment. Bioresour. Technol. 130, 248e255. http://dx.doi.org/10.1016/j.biortech.2012.12.025.
Taylor, J., 1998. Tencel e a unique cellulosic fibre. J. Soc. Dye. Colour. 114 (7e8), 191e193.
Woodings, C.R., 1995. The development of advanced cellulosic fibres. Int. J. Biol. Macromol. 17 (6), 305e309.
Zhang, W., Okubayashi, S., Bechtold, T., 2005. Fibrillation tendency of cellulosic fibers e part 4. Effects of alkali pretreatment of various cellulosic fibers. Carbohydr. Polym. 61 (4), 427e433.