Antibacterial polymer fibres by rosin compounding and melt-spinning


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1. Introduction

The increasing awareness of health hazards and also the pressure to rely on natural raw materials pushes traditional plastic producers to develop functionality using the 'chemistry of nature'. Moreover, the added functionality, such as antimicrobial response, opens up new business strategies for the current polymer industry. Antimicrobial response against several pathogens and, in detail, antibacterial activity in thermoplastics has not been surveyed. This work focuses on the processing of industrial grade purified rosin mixed with polyethylene (PE), polypropylene (PP), poly(lactic acid) (PLA), polyamide (PA) and corn starch based biopolymer (CS). Homopolymer masterbatches were extrusion-compounded and melt-spun to form fibres for a wide range of products, such as filters, reinforcements, clothing and medical textiles. Due to the versatile chemical structure of rosin, it was observed compatible with all the selected polymers. In general, the rosin-blended systems were shear-thinning in a molten condition. The doped fibres spun of PE and PP indicated adequate melt-spinning capability and proper mechanical properties in terms of ultimate strength and Young's modulus. The antibacterial response was found dependent on the selected polymer. Especially PE with a 10 wt% rosin content showed significant antibacterial effects against *Escherichia coli* DH5α and *Staphylococcus aureus* ATCC 12598 when analysed in the Ringer's solution for 24 h.

The antibacterial features of natural pine/spruce rosin are well established, yet the functionality in various thermoplastics has not been surveyed. This work focuses on the processing of industrial grade purified rosin mixed with polyethylene (PE), polypropylene (PP), poly(lactic acid) (PLA), polyamide (PA) and corn starch based biopolymer (CS). Homopolymer masterbatches were extrusion-compounded and melt-spun to form fibres for a wide range of products, such as filters, reinforcements, clothing and medical textiles. Due to the versatile chemical structure of rosin, it was observed compatible with all the selected polymers. In general, the rosin-blended systems were shear-thinning in a molten condition. The doped fibres spun of PE and PP indicated adequate melt-spinning capability and proper mechanical properties in terms of ultimate strength and Young's modulus. The antibacterial response was found dependent on the selected polymer. Especially PE with a 10 wt% rosin content showed significant antibacterial effects against *Escherichia coli* DH5α and *Staphylococcus aureus* ATCC 12598 when analysed in the Ringer's solution for 24 h.

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strong antibacterial effect on strains like S. aureus and E. coli but the mechanical properties decrease when compared to the reference polymers [20]. In contrast, wood resin, usually extracted of pine or spruce stock, can act as a source of antibacterial activity and also as chemical compatibilizer due to its chemically active structure that is rich in functionality [21–23].

Antibacterial characteristics of direct rosin extracts and rosin acid derivatives have been reported in the current literature. Rosin affects mainly Gram-positive bacteria and the abietic type acids of the rosin compounds have been reported to cause most of the response [24]. Even pure spruce wood particles have an antibacterial effect on E. coli, Streptococcus pneumoniae and Salmonella enterica [25]. It has been found that rosin affects the cell walls of bacteria, such as those of S. aureus, hindering the cells’ energy synthesis [26]. The source of resin, polymer additives, and the means of exposure of bacteria onto the rosin containing substance greatly affect the antibacterial response [27]. For packaging applications, rosin-PLA blends have been reported to be successfully antibacterial [28].

The use of rosin in industrially processed materials can face several challenges. First, part of the resin's chemical components degrade after reaching 200 °C whereas processing temperatures over 220–250 °C are required for extrusion and melt-spinning of PA. Even higher temperatures are needed to process high-performance fibres, such as those from poly(ethylene terephthalate) or not to mention poly(etherether ketone) [29,30]. The primary hypothesis of this work is that rosin-thermoplastic fibres have appropriate antibacterial activity. The secondary hypothesis is that polymers, namely PE, PP, PLA, PA, and corn starch biopolymer, can be compounded into masterbatches with rosin and further processed by using multi-filament melt-spinning. As a starting point, rosin is expected to be compatible with the homopolymers and the main interest is to understand the antibacterial response after fibre processing and the dependence of the antibacterial response on the bacterial contact, i.e., whether the samples are analyzed on agar gel or by continuously purging with an aqueous solution.

2. Experimental

2.1. Selected polymers and rosin

PE and PP granulates of a fibre spinning grade were acquired from Borealis Polymers. PLA (Ingeo), corn-starch polymer (Novamont) and PA (BASF) were acquired as industrial grade. The grades per selected polymer are given in Table 1. Commercial, industrial-grade rosin was provided by Forchem (Finland) and was pine rosin based extract gum rosin w/w (batch 16032017, acid value 167 mg KOH/g, softening point 74 °C) in the form of crushed particles.

2.2. Compounding and fibre melt-spinning

The homopolymer masterbatches were extrusion compounded with a model TSE 25 twin-screw extruder (Brabender). The resin was mixed with polyethylene (PE), polypropylene (PP), polyactic acid (PLA), corn-starch based polymer (CS) and polyamide 6 (PA) with a 10–20% resin content (per weight). Samples of masterbatches were separated for antibacterial studies and characterisation. The compounding and spinning batches with specific resin content were formed by mixing pure homopolymer granulates with the rosin-blended masterbatch; the different compounding and spinning series were coded with their polymer abbreviation, letter ‘r’ for spinning series, and target temperatures (at extruder) during melt-spinning. The different resin containing compounding and spinning batches are given in Tables 2 and 3, in addition to the references (i.e. PE, PP, PLA, CS, PA series) that did not contain any rosin. The compounds were melt-spun with a laboratory size melt-spinning machine (Fourné) with a fibre finish and drawing system including four godets and a spool for bobbin. For the spinning, a spinneret nozzle with 10 holes (hole diameter 0.5 mm) was used and, hence, a multifilament, which consists of ten fibres, was obtained. Prior to spinning PLA and PLA based blends, the PLA granulates were dried in an oven (60 °C) for a minimum of 12 h.

2.3. Polymer melt characterisation

The rheological behaviour of the compounds was studied using a model MCR 301 rotational rheometer (Anton Paar). A 25 mm-diameter cone-plate measuring system (CP25-4) was applied in a nitrogen atmosphere. Masterbatch granulates were used (rosin content 10–20 wt %) for constant shear rate tests where the shear rate was increased in logarithmic steps from 0.01 to 1001/s.

2.4. Rosin characterisation

Thermal degradation of rosin was studied using the thermo-gravimetric analysis (TGA) with a TG 209F3 (Netzsch) device by applying a constant heat ramp (10 °C/min) and nitrogen atmosphere. For all the resin characterisation, solid particles of rosin were directly applied in the as-received form. Subsequently, transition and melting temperatures were determined using differential scanning calorimetry (DSC) by using a model DSC 214 device (Netzsch). Sample (sample weight ≈8–20 mg) pans were sealed by a pierced aluminum lid and the analysis was performed in a nitrogen atmosphere (20–50 ml/min) and by applying a constant heat ramp (10 °C/min).

2.5. Fibre characterisation

2.5.1. Mechanical and physical properties

The effect of rosin compounding on the fibres’ stiffness and strength was studied using a tensile testing machine (Testometric, M500) with a 20 N load cell. A gauge length of 10 mm was applied. The tests were carried out at a 20 mm/min displacement rate in a standard environment; at a minimum 10 fibre samples were analysed per spinning batch. Before each mechanical test, the diameter of the fibre was measured using a microscope and used for (engineering) stress calculation. Visual light microscopy (by using DM 2500 M, Leica Microsystems) and scanning electron microscopy (SEM) using a field-emission gun electron microscope (ULTRAplus, Zeiss) were used for studying the fibre surfaces and polished cross-sections. The cross-sectional area, together with the force-strain data, was used to determine Young's modulus for each tested fibre. For moduli, a stress-threshold of 2.0 MPa was used and the strain-range for the linear approximation (fit by Least Squares method) was 0.0016 ± 0.0024 m/m for PE, PP and PLA. For PA and the CS series, a wider range was required due to the scatter of data and to reach a reliable fitting.

2.5.2. Rosin-polymer chemistry

Rosin, the PE homopolymer, fibre samples, and sample fixation epoxy (EpoFix, Struers) were characterized using Fourier transform infrared spectroscopy (FTIR) by using a Tensor 27 spectrometer (Bruker). The device was used in Attenuated Total Reflectance (ATR) mode, with a PIKE Technologies GladiATR accessory using a diamond crystal. The measured wavenumber range was 400–4000 cm⁻¹. 128 scans were used for both the background and sample measurements. The atomic force microscope and infrared (AFM-IR) data in this study were
obtained by using a NanoIR2S (Bruker/Anasys Instruments), coupled
with a multichip QCL source (MIRcat, Daylight Solutions; tunable re-
petition rate range of 0–500 kHz; spectrum resolution of 0.1 cm$^{-1}$)
covering the range from 900 till 1800 cm$^{-1}$. An Au-coated silicion
probe (contact AFM-IR, cantilever, Anasys Instruments) was employed.
The rosin-PF fibres samples for AFM-IR were first embedded in epoxy by
casting (EpoFix, Struers). After the casting, 100–150 nm thick slices
were cut of a pure rosin-PF fibre cross-section by using a cryo-ultra-
microtome (Leica Ultracut 7) at −80 to −100 °C. The slices from
random locations and depth from a fibre sample were captured on
copper grids covered by a carbon film (Electron Microscopy Sciences).
The grids with samples were mounted on metallic chips (Ted Pella) for
AFM.

2.6. Antibacterial activity

Antimicrobial activity of the polymer samples was tested against
indicator bacteria E. coli DH5α and S. aureus ATCC 12598. The indi-
cators were cultured at 37 °C in lysogeny broth (LB), with 1.5% agar
for solid media. Antibacterial tests were performed in both agar media
and in Ringer’s solution of 1/4 strength (mixture of NaCl, KCl, CaCl$_2$,
NaHCO$_3$ and distilled water).

2.6.1. Soft-agar overlay technique

The indicator strains were first cultured overnight in LB broth.
200 μl of the cultures were mixed in 10 ml of melted LB soft-agar
(0.75% agar) in a glass tube. Small pieces of granulates and fibres to be
tested were put onto a LB agar plate, and the soft-agar containing the
indicator bacteria was poured onto the plate. The plates were incubated
o/n at 37 °C, after which the possible inhibition zones around the
sample pieces were observed.

2.6.2. Antimicrobial activity in liquid

The indicator bacteria were first cultured overnight in LB broth.
Colony forming units per ml of the o/n cultures were determined by
serial dilutions in 1/4 strength Ringer’s solution and plating onto LB
agar. From the serial dilutions of $10^2$–$10^4$, 1 ml (about $10^5$–$10^7$ cfu/ml)
was used for the antimicrobial tests by mixing with 0.5 g of sample
granulates or 0.1 g of fibres in 2-ml Eppendorf tubes. The mixtures were
incubated for 24 h at room temperature in a rotator (22 rpm). After
incubation, the samples were serially diluted in 1/4 strength Ringer’s
solution, and plated onto LB agar for determining the bacterial survival
by colony counting. All the experiments were performed in triplicates.

3. Results

3.1. Rosin analysis

Rosin DSC and TGA curves are shown in Fig. 1. Based on the DSC,
rosin melts after the softening at $\approx 40 °C$ following essentially constant
behaviour until the liquid phase. The multiple peaks or nonlinearity in
the flux curve indicates the natural variation of rosin—the softening
point given by the material provider was 74 °C. The variation in the flux
over the temperature range of $\approx 50–100 °C$ presumably also relates to

Table 2
Rosin-polymer blend batches for extrusion compounding (series name always refers to the melt-spinning temperature).

<table>
<thead>
<tr>
<th>Polymer</th>
<th>Rosin content (wt%)</th>
<th>Compounding temperature (°C)</th>
<th>Test series</th>
</tr>
</thead>
<tbody>
<tr>
<td>PE</td>
<td>10, 20</td>
<td>205, 205, 160</td>
<td>PE10-180, PE20-180, PE10-160</td>
</tr>
<tr>
<td>PP</td>
<td>10, 20</td>
<td>205, 205, 160</td>
<td>PP10-200, PP20-200, PP10-160</td>
</tr>
<tr>
<td>PLA</td>
<td>10, 20</td>
<td>160</td>
<td>PLA10, PLA20</td>
</tr>
<tr>
<td>CS</td>
<td>10</td>
<td>130–135</td>
<td>CS10</td>
</tr>
<tr>
<td>PA</td>
<td>10</td>
<td>223</td>
<td>PA10</td>
</tr>
</tbody>
</table>

* Reference homopolymer PLA fibre spun at 190–200 °C.
* Reference homopolymer PA fibre spun at 230 °C.

Table 3
Rosin-polymer blend batches for fibre melt-spinning.

<table>
<thead>
<tr>
<th>Polymer</th>
<th>Rosin content (wt%)</th>
<th>Temperature for spinning (°C)</th>
<th>Test series</th>
</tr>
</thead>
<tbody>
<tr>
<td>PE</td>
<td>10, 20</td>
<td>180, 180, 160</td>
<td>PE10-180, PE20-180, PE10-160</td>
</tr>
<tr>
<td>PLA</td>
<td>10, 20</td>
<td>160–180$^a$</td>
<td>PLA10, PLA20</td>
</tr>
<tr>
<td>CS</td>
<td>10</td>
<td>169</td>
<td>CS10</td>
</tr>
<tr>
<td>PA</td>
<td>10</td>
<td>220$^b$</td>
<td>PA10</td>
</tr>
</tbody>
</table>

$^a$ Reference homopolymer PLA fibre spun at 190–200 °C.
$^b$ Reference homopolymer PA fibre spun at 230 °C.

Fig. 1. Thermal analysis of the rosin batch (particles as-received): (a) DSC curve (no background extraction) and; (b) TGA curve for the pure rosin.
the removal of moisture and solvent-type components as well as possible slight crystallinity. The TGA curve (Fig. 1(b)) shows that the final degradation occurs over a temperature range of \(\approx 220-450^\circ C\) (onset \(\approx 140^\circ C\)), which suggests that rosin in the melt-spinning process of PA fibres (220 °C) might have partly degraded.

### 3.2. Compound behaviour

Rosin and raw polymer granulates were mixed in the extruder by directly feeding both components into the extruder’s hopper. The compounding was carried out at ambient laboratory conditions. The blending of the components was assessed by monitoring the color change of the blend, possible clinging and spitting of rosin either at the hopper or nozzle of the extruder. Rosin was observed to mix readily with thermoplastics and the masterbatches were smooth composites by visual observation with a slight yellowish color. The extruded blend yarn was cut into granulates for further melt-spinning and characterisation.

The behaviour of the blended polymer-rosin systems was studied in terms of the viscosity at different shear rates. The viscosity curves are shown in Fig. 2(a)–(d). The behaviour of different homopolymers was as expected and the changes due to rosin inclusion mostly were established by a significant decrease in viscosity at higher shear rates. Here, all the compounded melts were shear-thinning—yet the viscosity remained essentially constant until a high shear rate level (> 10 \(^1/s\)) for PE, PP and PLA homopolymers—noting that typical shear rate range during melt-spinning (at nozzle) can reach even \(10^3 \, 1/s\) values. The addition of rosin clearly emphasises the shear-thinning behaviour and, for PLA and CS (Mater Bi polymer), leads to a decade-lower viscosity compared to the homopolymer as a starting point.

Interestingly, the character of PE melt with a rosin content was clearly dependent on the (measurement) temperature. For a higher measurement temperature (180 °C) and higher (20%) rosin content, the viscosity decreased at high shear rates—probably the rosin phase in the compound disintegrates and works as a lubricant. Similar behaviour emerged with PP, measured at 180 °C, but already for a 10% rosin content. This might suggest that the compatibility between rosin and PP is not as good as for PE or the component of lower viscosity (rosin) may act as ‘lubricant’ and emerge unevenly during the processing at different temperatures. Also, for all the polymer compounds, the viscosity-shear rate dependance seems nonlinear and two plateaus, or shifts, can be distinguished: the first sharp decrease at \(\approx 0.1 \, 1/s\) and another at
≈ 10 1/s shear rate. It should be noted that polymers may suffer from edge fracture during rotational rheometer measurements at shear rates above the range of 1 to 10 1/s (depending on the polymer and its viscosity) and the measured absolute viscosities therefore appear smaller than they actually are.

### 3.3. Fibre spinnability and quality

The fibre spinning trials were performed by applying machine parameters (e.g. godet temperatures and speeds) based on experience and initial trials with the rosin-containing blends and a minimum cold-drawing by godets was applied. The fibre characteristics for each successful fibre series are given in Table 4 and stress–strain curves in Figs. 3 and 4. The first actual trials were run by using the PE and PP masterbatches as well as melt temperatures of 180 °C and 200 °C (at screw), respectively. For the PE and PP mixed with masterbatches with 10% and 20% rosin content, the melt-spinning of fibres was successful, in terms of fibre diameter (63–100 μm) and spinnability (melt draw ratio ≈ 65). Based on the compounding difficulties in spinning with a 20% rosin content, the PLA, CS and PA series were studied only for a 10% rosin content. The spinning and collection of PLA fibre was challenging as indicated by the significant decrease in viscosity due to rosin blending (see Fig. 2(d)). PLA based fibres lost 66–68% of their strength due to rosin doping, independent of whether the fibre was drawn (on godets) or not. The PLA-rosin fibres were brittle with a negligible ductility (elongation to break ≈ 6%). Similarly to PLA, the starch polymer based fibres (CS) suffered a significant negative effect due to rosin—in contrast to the PLA fibres, the rosin blending with the CS series plastic led to a very low strength while elongation to break remained essentially unchanged, i.e. the fibre stiffness significantly

<table>
<thead>
<tr>
<th>Series</th>
<th>Mean diameter and deviation (μm)</th>
<th>Mean strength and deviation (MPa)</th>
<th>Logarithmic strain at break (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPE-180</td>
<td>71 ± 7</td>
<td>41 ± 20</td>
<td>308 ± 123</td>
</tr>
<tr>
<td>IPE10-180</td>
<td>76 ± 25</td>
<td>19 ± 11</td>
<td>250 ± 118</td>
</tr>
<tr>
<td>IPE20-180</td>
<td>100 ± 30</td>
<td>17 ± 7</td>
<td>279 ± 106</td>
</tr>
<tr>
<td>IPE-160</td>
<td>53 ± 8</td>
<td>63 ± 17</td>
<td>251 ± 67</td>
</tr>
<tr>
<td>IPE10-160</td>
<td>51 ± 7</td>
<td>61 ± 26</td>
<td>279 ± 113</td>
</tr>
<tr>
<td>fPP-200</td>
<td>72 ± 11</td>
<td>126 ± 42</td>
<td>263 ± 97</td>
</tr>
<tr>
<td>fPP10-200</td>
<td>63 ± 20</td>
<td>95 ± 41</td>
<td>234 ± 102</td>
</tr>
<tr>
<td>fPP20-200</td>
<td>71 ± 31</td>
<td>46 ± 23</td>
<td>223 ± 90</td>
</tr>
<tr>
<td>fPP-160</td>
<td>47 ± 10</td>
<td>180 ± 73</td>
<td>210 ± 58</td>
</tr>
<tr>
<td>fPP10-160</td>
<td>57 ± 9</td>
<td>114 ± 32</td>
<td>216 ± 84</td>
</tr>
<tr>
<td>fPLA</td>
<td>55 ± 6</td>
<td>153 ± 47</td>
<td>137 ± 47</td>
</tr>
<tr>
<td>fPLA10</td>
<td>84 ± 14</td>
<td>52 ± 15</td>
<td>16 ± 7</td>
</tr>
<tr>
<td>fPLA10c</td>
<td>116 ± 7</td>
<td>49 ± 5</td>
<td>3 ± 0</td>
</tr>
<tr>
<td>fCS</td>
<td>56 ± 5</td>
<td>33 ± 12</td>
<td>177 ± 59</td>
</tr>
<tr>
<td>fCS10</td>
<td>59 ± 6</td>
<td>9 ± 4</td>
<td>156 ± 59</td>
</tr>
<tr>
<td>fPA</td>
<td>55 ± 7</td>
<td>120 ± 39</td>
<td>233 ± 74</td>
</tr>
<tr>
<td>fPA10</td>
<td>52 ± 7</td>
<td>120 ± 40</td>
<td>244 ± 78</td>
</tr>
</tbody>
</table>

* Simply melt-spin fibre, not drawn on godets.

Fig. 3. Stress–strain behaviour of different melt-spun fibres with rosin: (a) IPE-180, IPE10-180 and IPE20-180 series fibres; (b) IPE-160 and fPE10-160 series fibres; (c) fPP-200, fPP10-200 and fPP20-200 series fibres; (d) fPP-160 and fPP10-160 series fibres.
decreased due to rosin in the polymer structure. The PA blends did not suffer any observable strength decrease due to a 10% rosin content compared to the pure homopolymer counterpart.

The stiffness of the spun fibres, in terms of Young's modulus, can indicate good initial compatibility of rosin and the polymer when high values and low scatter of results are reached. The average modulus values and relative deviations for modulus and ultimate strength are given in Table 5. For PE, PP and PLA, the modulus values agree with typical homopolymer moduli and the scatter in the modulus values is clearly lower than in the ultimate strength values—as was expected. Rosin had an effect to decrease the stiffness values and tended to increase the scatter in the modulus values—the effect was stronger the higher the rosin amount. For the PE and PP series, the higher processing temperature led to a lower strength but similar trend for stiffness could not be seen. Presumably, a high processing temperature ruptures the polymer's molecular structure that is reflected to the ultimate behaviour (especially for PP). For PA and the CS series, the modulus values are low and mainly refer to poor quality of the blend where the rosin as well as fibre surface act as voids leading to early yielding and breakage. Based on the mechanical analysis, the spun PE and PP series fibres were the most potential for further analysis (with optimum rosin content ≈ 10–20%).

### 3.4. Antibacterial activity

The antimicrobial activity of the melt-spun fibres was determined against both Gram-negative and Gram-positive indicator bacteria *E. coli* and *S. aureus*, respectively. The soft-agar was seeded with the indicators, and overlaid to the plastic samples on agar plate. The rosin-containing fibre samples caused small but rather clear inhibition zone

<table>
<thead>
<tr>
<th>Fibres</th>
<th>Mean modulus and deviation (GPa)</th>
<th>COV (%) over moduli</th>
<th>COV (%) over strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>fPE-180</td>
<td>0.89 ± 0.36</td>
<td>40</td>
<td>49</td>
</tr>
<tr>
<td>fPE10-180</td>
<td>0.47 ± 0.33</td>
<td>71</td>
<td>58</td>
</tr>
<tr>
<td>fPE20-180</td>
<td>0.73 ± 0.42</td>
<td>57</td>
<td>41</td>
</tr>
<tr>
<td>fPE-160</td>
<td>0.53 ± 0.13</td>
<td>25</td>
<td>27</td>
</tr>
<tr>
<td>fPE10-160</td>
<td>0.75 ± 0.22</td>
<td>29</td>
<td>43</td>
</tr>
<tr>
<td>fPP-200</td>
<td>0.97 ± 0.11</td>
<td>11</td>
<td>33</td>
</tr>
<tr>
<td>fPP10-200</td>
<td>0.81 ± 0.35</td>
<td>43</td>
<td>43</td>
</tr>
<tr>
<td>fPP20-200</td>
<td>0.40 ± 0.32</td>
<td>79</td>
<td>50</td>
</tr>
<tr>
<td>fPP-160</td>
<td>1.23 ± 0.49</td>
<td>40</td>
<td>41</td>
</tr>
<tr>
<td>fPP10-160</td>
<td>0.91 ± 0.36</td>
<td>40</td>
<td>28</td>
</tr>
<tr>
<td>fPLA</td>
<td>2.07 ± 0.45</td>
<td>22</td>
<td>31</td>
</tr>
<tr>
<td>fPLA10</td>
<td>1.80 ± 0.41</td>
<td>23</td>
<td>29</td>
</tr>
<tr>
<td>fCS</td>
<td>0.21 ± 0.03</td>
<td>15</td>
<td>36</td>
</tr>
<tr>
<td>fCS10</td>
<td>0.07 ± 0.01</td>
<td>15</td>
<td>44</td>
</tr>
<tr>
<td>IPA</td>
<td>0.24 ± 0.06</td>
<td>26</td>
<td>33</td>
</tr>
<tr>
<td>fPA10</td>
<td>0.48 ± 0.22</td>
<td>44</td>
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</tr>
</tbody>
</table>

Fig. 4. Stress-strain behaviour of different melt-spun fibres with rosin: (a) fPLA and fPLA10 series fibres; (b) fCS and fCS10 series fibres; (c) fPA and fPA10 series fibres.

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with *S. aureus* in soft-agar, but no inhibition could be seen against *E. coli*.

The soft-agar overlay method may not be perfect for studying the fibres and granulates, as the rosin is practically insoluble in water, it does not diffuse well in agar, and thus the bacteria are killed only when in close proximity of the sample. In addition, reliable and comparable data is difficult to obtain from small inhibition zones. Therefore, the antimicrobial activity of the polymeric samples were tested in liquid with rotation, when the thermoplastic and the bacteria are in motion, and the bacteria can get in physical contact with the polymer surface. After rotating 24 h of the sample-bacteria mixture, the survival of the bacteria was determined by plate counting. All the rosin containing granulates except for PP and PLA killed *S. aureus* significantly but the effect was much less with *E. coli*, as shown in Fig. S. In the fibre form, fPE10 and fPA10 samples were ‘effective’ against *S. aureus*, whereas PP was clearly less effective. Only PE and PA fibres with a 10% of rosin could inhibit *E. coli* to some extent, but the inhibition was remarkably less than against *S. aureus*.

### 3.5. Polyethylene-rosin miscibility

The antibacterial results indicated the superiority of PE based fibres against *S. aureus* and *E. coli*. However, it is not well understood how rosin interacts with the molecular network in fibres. SEM imaging shows essentially smooth fibre cross-sections (Fig. 6) and does not indicate any microscopic, separate, rosin phases. Further analysis was carried out for the PE-rosin system via FTIR and nano-IR studies (casting epoxy spectrum given in supplement material). Raw data of the FTIR for epoxy as well as for the presented plots are available for readers [31].

In Fig. 7(a), it can be seen that the addition of rosin leads to absorption of CH\textsubscript{3} stretch and bend related bands (2956, 2867 and
1384 cm\(^{-1}\), respectively). Based on the pure rosin and pure PE raw material granulates’ FTIR spectra (Fig. 7(b)), the appearance of CH\(_3\) related peaks tend to originate from rosin, as well as do the strong absorption at 1690 cm\(^{-1}\) and 1272 cm\(^{-1}\) from C=O and C-O bond stretch, respectively. Coinciding with the CH\(_3\) absorption bands, the rocking motion related band from multiple CH\(_2\) groups at 715 cm\(^{-1}\) is no longer detected in the spectrum (in Fig. 7(a)).

The AFM-IR results are shown for PE-rosin fibre samples in Fig. 8. The rosin is distributed essentially in an even manner. Possible rosin-rich areas (‘mixed spectrum’) were considered (Fig. 8(b)) yet the spectra do not match those of pure rosin making it unreliable to conclude whether or not local accumulation exists on a sub-nano scale.

4. Discussion

The core of this study is the application of rosin-blended thermoplastic compounds for continuous, melt-spun multifilaments. Therefore, the first task was to analyse the general spinnability in terms of the viscosity of the melts. Since all the selected plastics can be melt-spun below the deterioration temperature of rosin (above 220 °C, Fig. 1), they are applicable as a starting point. However, industrial melt-spinning of fibres requires high enough throughput of properly drawn fibres with properly adjusted balance between strength and elongation (strain to break). In this study, the spun fibres were not drawn to specifically optimised strength–stiffness ratio and, therefore, the strain-hardening behaviour, indicating a good potential to orient and strengthen the polymer, is important. For the homopolymer fibres, basically all the polymers showed strain-hardening behaviour during the tensile tests. For the compounds with rosin (10%), PLA and the corn starch-based biopolymer lost basically all the strain-hardening ability in addition to a dramatic decrease in the fibres’ ultimate strength. The degradation of PLA during any high-temperature processing is well-known\(^{[32,33]}\) yet the addition of rosin tends to only strengthen this behaviour. Anyhow, various doped PLA compounds can be melt-spun successfully for high take-up velocities when the system is properly controlled in terms of dried source granulates and spinning parameters\(^{[34,35]}\). In contrast to PLA, the PE, PP and PA fibres in this study were characterised by a very high elongation to break and high ultimate strength values with significant strain-hardening—for the homopolymers as well as for the rosin-containing systems. Especially for the PE-rosin spinning at a lower (160 °C) temperature, the rosin addition did not observably decrease the fibre strength and even increased (40%) the initial stiffness (Young’s modulus).

In the current literature, PE/PA-rosin systems for industrial fibre production have not been studied. In general, PP is relatively difficult to modify since it is non-polar, hydrophobic and highly crystalline—there are very few attempts to use it for any antibacterial product; cupric oxide doping has been found effective against E. coli\(^{[36]}\). In contrast to PP, antibacterial activity in PA and PE fibres has been accomplished with a variety of means\(^{[2,4,37]}\). For other than fibre-form products, e.g. in adhesive applications, good chemical compatibility between PE phases and rosin derivatives (terpenes) has been reported\(^{[38,39]}\).

5. Conclusions

This work presents the results of rosin–polymer compounds’ viscosity, overall processing effects by temperature and rosin content, fibre performance, and the two-stage analysis of the antibacterial response against indicator bacteria E. coli DH5\(_\alpha\) and S. aureus ATCC 12598. The compounds involve rosin mixed with polyethylene (PE), polypropylene (PP), polylactic acid (PLA), polyamide (PA) and starch based biopolymer (CS). The fibres made of PE and PP indicated the best mechanical
response in terms of initial stiffness (Young’s modulus) and ultimate strength and strain and, thus, the highest potential to be optimized for specific applications. The PLA-rosin fibres reached a high stiffness level but the degradation of the PLA network during processing led to a low ultimate strength and strain. For all the fibre series, the addition of rosin tended to decrease the initial stiffness—PE-rosin fibres indicated the least stiffness degradation and the highest compatibility. Along with the mechanical response, the antibacterial function was found highly dependent on the selected polymer and the type of bacteria as well as the environment of intended (tested) antibacterial effect. PE fibres with a 10 wt% rosin content was verified to show a high antibacterial effect against S. aureus (−100%) and a clear effect against E. coli (−54%).

Conflict of interest

None.

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