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Biodegradable Aliphatic-Aromatic Polyesters:
“Ecoflex™”

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1 Introduction

1.1 Perspectives for Biodegradable Plastics

The market for biodegradable materials is growing significantly every year. A positive reaction can be expected from those applications, where the biodegradability offers a clear advantage for customers and the environment, with typical examples being packaging, compost bags, agricultural films, and coatings. However, in order to gain wider acceptance in the market for such innovative solutions, the following requirements must be fulfilled:

- Good properties and processability comparable with that of conventional plastics.
- Competitive prices and supply in sufficient quantities, taking advantage of economies of scale.

BASF has risen to this challenge, and in 1998 a special type of biodegradable copolyester based on synthetic raw materials was commercialized by the company under the tradename Ecoflex®. With Ecoflex®, BASF aims to make an active contribution to the development of the market for biodegradable polymers. Following analysis of the existing market and promising applications, it is estimated that good opportunities exist especially for the successful development of large volumes in materials such as compost bags, fast food/disposables, agricultural films, hygiene films, and paper coatings.

2 Historical Outline

In 1990, at the request of the German state government, BASF began a feasibility study of biodegradable and compostable plastics for use of packaging. This study revealed that the most important factors for the biodegradable plastics for commercial uses are price, performance, availability of monomers/polymers, and use of existing plant. On the basis of these prerequisites, BASF began screening suitable monomers on the laboratory scale. Pilot plant production and sampling of Ecoflex® were started in 1994 and, in 1997, following a good response from several customers, BASF began to produce Ecoflex® commercially at an existing poly(butylene terephthalate) (PBT) plant.

3 Structure of Ecoflex®: The BASF Concept of Modular Units

Ecoflex® is an aliphatic-aromatic copolyester based on terephthalic acid, adipic acid, 1,4-butanediol and modular units.

The product properties of Ecoflex® are designed to meet the requirements of a biodegradable plastic: ideally, a combination of processability, utilization properties, and biodegradability. This is achieved by the synthesis of tailor-made molecular structures, obtained through modular units by
which the statistical copolyester units, including 1,4-butanediol and the dicarboxylic acids, adipic acid and terephthalic acid, are linked (Figure 1).

This modular system involves the incorporation of hydrophilic components of monomers with branching, leading to chain-lengthening, and thereby increasing the molecular weight to yield tailor-made products with totally different material properties.

4 Properties, Processing, and Application of Ecoflex

Examples of the mechanical properties, processing (rheological) properties and applications of Ecoflex are outlined in the following sections.

4.1 Property Profile of Ecoflex

The mechanical properties of Ecoflex are comparable with those of poly(ethylene)-low density (PE-LD) (Tables 1 and 2). The films are tear-resistant and flexible, and also resistant to both water and fluctuations in humidity. The extreme strength and failure energy are clear product characteristics of Ecoflex, and these significantly exceed the respective properties of PE-LD films. The barrier properties differ from those of PE-LD, however; Ecoflex films are breathable because of their moderate water vapor permeability, and this can be adjusted within different Ecoflex-batches (Tables 3 and 4).

4.2 Processing of Ecoflex

4.2.1 Film Extrusion

Ecoflex can be processed by conventional blown film lines for PE-LD. The excellent draw-down ability of Ecoflex (Figures 2 and 3) leads to interesting applications in the thin film segment (<20 μm) and, depending on the processing equipment available, 10 μm films can be obtained.

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Tab. 1 Typical basic material properties of Ecoflex

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>Test method</th>
<th>Ecoflex</th>
<th>Lupolen 2420 F (PE-LD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass density</td>
<td>g cm⁻³</td>
<td>ISO 1183</td>
<td>1.25–1.27</td>
<td>0.922–0.925</td>
</tr>
<tr>
<td>Melt flow rate</td>
<td>ml 10 min⁻¹</td>
<td>ISO 1133</td>
<td>3–8</td>
<td>–</td>
</tr>
<tr>
<td>MVR 190 °C, 2.16 kg</td>
<td>g 10 min⁻¹</td>
<td>–</td>
<td>–</td>
<td>0.6–0.9</td>
</tr>
<tr>
<td>MFR 190 °C, 2.16 kg</td>
<td>°C</td>
<td>DSC</td>
<td>110–115</td>
<td>111</td>
</tr>
<tr>
<td>Shore D hardness</td>
<td>–</td>
<td>ISO 868</td>
<td>32</td>
<td>48</td>
</tr>
<tr>
<td>Vicat VST A/50</td>
<td>°C</td>
<td>ISO 306</td>
<td>80</td>
<td>96</td>
</tr>
</tbody>
</table>

\( T_m \): melting point; \( T_g \): glass transition temperature.
Ecoflex does not require any special handling; neither is the pre-drying usually associated with thermoplastic polyesters necessary with Ecoflex, and this provides an additional advantage for the converter.

Films made from Ecoflex can be printed and welded with conventional equipment used with PE-LD.

Hence, Ecoflex is an outstanding material for applications such as compost bags, films in the agricultural sector, or hygiene films.

### 4.2.2 Master Batches of Ecoflex

For extrusion processing, the production of colored films, adjustment of the water vapor barrier, antiblock and slip properties, and transparency, master batches based on Ecoflex were developed to fulfill the different customers needs (Table 3).

The barrier properties of Ecoflex films can be adjusted by using special additives. Water vapor permeabilities of Ecoflex films produced with different master batches are listed in Table 4.

### Tab. 2 Typical properties of blown film (50 μm) of Ecoflex®

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>Test method</th>
<th>Ecoflex®</th>
<th>Lupolen® 2420 F (PE-LD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transparency</td>
<td>%</td>
<td>ASTM D 1003</td>
<td>82</td>
<td>89</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>N mm⁻²</td>
<td>ISO 527</td>
<td>32/36</td>
<td>26/20</td>
</tr>
<tr>
<td>Ultimate strength</td>
<td>N mm⁻²</td>
<td>ISO 527</td>
<td>32/36</td>
<td>–</td>
</tr>
<tr>
<td>Ultimate elongation</td>
<td>%</td>
<td>ISO 527</td>
<td>580/820</td>
<td>300/600</td>
</tr>
<tr>
<td>Failure energy</td>
<td>J mm⁻¹</td>
<td>DIN 53373</td>
<td>14.3</td>
<td>5.5</td>
</tr>
<tr>
<td>Tear propagation resistance</td>
<td>N mm⁻¹</td>
<td>DIN 53363</td>
<td>236/124</td>
<td>–</td>
</tr>
<tr>
<td>Permeation rates:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oxygen</td>
<td>Cm³ (m⁻² · d · bar)</td>
<td>DIN 53380</td>
<td>1600</td>
<td>2900</td>
</tr>
<tr>
<td>Water vapor</td>
<td>g (m⁻² · d)</td>
<td>DIN 53122</td>
<td>140</td>
<td>1.7</td>
</tr>
</tbody>
</table>

### Tab. 3 Masterbatches of Ecoflex®

<table>
<thead>
<tr>
<th>Batch type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ecoflex® Batch SL1</td>
<td>Slip agent (erucamide)</td>
</tr>
<tr>
<td>Ecoflex® Batch SL2</td>
<td>Slip agent (wax-type)</td>
</tr>
<tr>
<td>Ecoflex® Batch AB1</td>
<td>Antiblock agent (fine talc)</td>
</tr>
<tr>
<td>Ecoflex® Batch AB2</td>
<td>Antiblock agent (coarse talc)</td>
</tr>
<tr>
<td>Ecoflex® Batch C White</td>
<td>White masterbatch</td>
</tr>
<tr>
<td>Ecoflex® Batch C Black</td>
<td>Black masterbatch</td>
</tr>
</tbody>
</table>

### Tab. 4 Water vapor permeability of Ecoflex® films

<table>
<thead>
<tr>
<th>Film thickness [μm]</th>
<th>Water vapor permeability [g m⁻² · d]</th>
<th>Water vapor permeability [g (100 μm) · m⁻² · d]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ecoflex®</td>
<td>15</td>
<td>&gt; 500</td>
</tr>
<tr>
<td>Ecoflex® + SL2</td>
<td>16</td>
<td>200</td>
</tr>
<tr>
<td>Ecoflex® + SL2 + AB1</td>
<td>14</td>
<td>170</td>
</tr>
</tbody>
</table>
4.3 Applications

Typical applications of Ecoflex are compost bags for organic waste, films in the agricultural sector, household films, and coating or lamination (e.g., paper), and coating materials for starch-based products (e.g., plates, cups) within the fast food and catering industries.

Fig. 2 Melt elongation of Ecoflex at 130 °C.

Fig. 3 Viscosity functions of Ecoflex at different temperatures.
4.3.1 Compost Bags for Organic Waste
Kitchen waste can be collected hygienically and composted together with a biodegradable bag. Ecoflex® meets the requirements of compost bags; these include in particular the wet strength of the film and the time over which it remains stable to the organic waste, as well as problem-free processing in the compost facility.

4.3.2 Mulch Films
Uses of mulch covers include earlier harvesting, higher yields, and better crop quality. The advantage of mulch films made from biodegradable plastics such as Ecoflex® is that, following the harvest they can simply be ploughed together with the plant residue into the soil, where they fully degrade.

4.3.3 Coated or Laminated Materials
Coating or lamination of, for example, paper is used when there is a need for high wet strength and fat resistance. The use of Ecoflex® as a biodegradable laminate offers the additional advantage of problem-free disposal by composting. Applications of particular interest are therefore packaging materials soiled with food residues, such as paper wraps, drinking cups, fast-food packaging, or boxes and containers for frozen food.

4.3.4 Oriented Films
Like other thermoplastic polyesters, Ecoflex® shows a high orientability-enhanced mechanical properties. Consequently, orientated films and monofilaments are interesting applications for Ecoflex® where biodegradability is an advantage (e.g., knitted nets).

4.3.5 Transparent Films for Food Wrapping (Cling Films)
By adding special additives and optimizing the processing conditions, transparent films can be obtained using a blown film process. These films can be used for the wrapping of foodstuffs, including meats, vegetables and fruits sold in supermarkets.

4.4 Starch Ecoflex® Blends
Starch is an inexpensive raw material that is available in large quantities. The disadvantage, however, is that native starch cannot be processed like thermoplastic materials without the need for additives. Moreover, starch materials have a somewhat limited range of application due to their relatively high water absorbing properties. Blending starch with a hydrophobic polymer makes it possible to overcome these disadvantages, but clearly in order to create completely biodegradable starch blends it is crucial to use biodegradable hydrophobic polymers.

The use of Ecoflex® for starch blends leads to the targeted hydrophobization of the starch, and achieves the water-resistance that such blends require in many applications. Films made from this material show good mechanical properties such as high ultimate strength and elongation at break, they are antistatic, permeable to oxygen and water vapor, can be printed on and sealed, and they are very soft to the touch. Thus, Ecoflex® is an essential component for the processing of renewable materials such as starch; consequently, BASF is supplying Ecoflex® to several starch blend producers in Europe.

5 Biodegradation and Ecotoxicity of Ecoflex®
The copolyester Ecoflex® combines the good material properties of aromatic polyesters...