*Macromol. Symp.* ***135,*** *97-111 (1998)* 

# Innovative Concept for the Upgrading of Recyclates by Restabilization and Repair Molecules

Rudolf Pfaendner*, Heinz Herbst, Kurt Hoffmann
CIBA Spezialitätenchemie GmbH, Polymer Design & Recycling
D-68619 Lampertheim, Germany

The role of additives in creating tailor-made plastics and in generating innovative products is commonly accepted. Stabilizers, pigments, lubricants, impact modifiers and other additives enable safe and effective processing and guarantee, for example, mechanical properties and appearance appropriate for the required service time.
Recycled plastics still suffer from the imputation of being of low value and, consequently, acceptable only for "second-hand" applications. The concept of restabilization and repair has been introduced in order to provide recyclates with properties similar to those in their original use ("closed loop") or to upgrade them to high-value applications, thus providing a potential substitute for virgin materials. Supplying the necessary processing and long-term stability of the recyclate including elimination of the negative influence of prodegradants and of impurities are the key factors of this idea.
The concept presented here comprises the development of an appropriate formulation for recyclates taking into consideration both the materials source and the targeted application. It may be classified into four scenarios:
– Closed-loop applications from clearly defined sources (e.g., bottle crates, waste bins, automotive parts) require a carefully adjusted restabilization system with sufficient amounts of processing, light, and heat stabilizers. At least the part of stabilizers used up in the first life has to be compensated.
– The formulation of recyclates in applications different from the original ones depends clearly on the requirements. For instance, a recyclate from packaging applications utilized in long-term applications is only attainable by means of the addition of heat and/or light stabilizers. The type and amount of the suitable stabilizer system have to be defined according to the material (e.g., PP, HDPE, blends), the targeted lifetime and the application area (e.g. outdoor), above all, however, the final product itself (e.g., thick posts or thin films).
– If impurities such as paint residues, printing inks or a heavily degraded material cause severe problems with respect to processing and material properties, the addition of reactive compounds can compensate their negative contribution. For example, selected oxirane key compounds are able to eliminate to a great extent the detrimental influence of paint residues in PP/EPDM bumper materials on the mechanical and long-term heat properties of the material.
– Recyclates of condensation polymers such as polyamides and polyesters as well as their blends are degraded mainly by hydrolytic cleavage of the polymer chains. The reduced molecular weight can result in inferior properties rendering certain applications impossible. However, difunctional oxirane compounds in combination with catalytically active accelerators can entirely repair the predegradation through a chain-extension process.
The concept of restabilization and of repair molecules has been translated into a proprietary product line (®Recyclostab, ®Recyclossorb, ®Recycloblend) specially designed for the upgrading of recyclates and, therefore, offering decisive benefits for the processor, compounder and the recycling industry.
Examples from different industrial areas (packaging, automotive, electronic, transport) verify that properly stabilized products can satisfy any requirements for extended product life and appearance in a wide variety of applications.

## MECHANICAL RECYCLING AND THE SUBSTITUTION FACTOR

In the years to come, the integrated approach to waste management will encourage an enormous increase in mechanical recycling, feedstock recycling as well as energy recovery. In the same period, the amount of plastic waste which is currently disposed of on landfill sites will have to be and will be drastically reduced. Mechanical recycling of post-user plastic waste accounted for 8.6 % of all plastics waste in 1995 [1]. According to experts, this rate is expected to increase to 15-25 % during the next ten

 CCC 1022-1360/98/$ 17.50

years. As a result, markets for particular products, which have invariably been dominated by virgin plastics, will increasingly be opened to this flow of recyclate.

In terms of economical and ecological performance, single plastics and mixed plastics with an exactly defined composition and low levels of impurities are best suited for mechanical recycling. Provided the recovered recyclate is able to substitute virgin material, a one-for-one mechanical recycling is the most energy-efficient of the various recycling options. The so-called "substitution factor" would in this case equal unity, meaning that the recyclate would have the same functional properties as the comparable virgin material. Under these circumstances, mechanical recycling not only requires least energy, compared to other recycling processes, but also has the lowest emissions [2]. These advantages decrease with a lower substitution factor.

## STRUCTURAL INHOMOGENEITIES AND IMPURITIES IN RECYCLATES

Why do recyclates and virgin materials behave differently? Except in the case of a few clearly defined production waste types, there are various fundamental differences between virgin material and recyclate.

Structural inhomogeneities and residual impurities are present even if a recyclate is carefully sorted, separated and cleaned [3]. Already during first processing of the virgin plastic and its first life, irreversible changes of the polymer chain take place, induced mechanochemically, chemically or by radiation. Through carbon-centered (alkyl) or oxygen-centered (alkylperoxyl, alkoxyl, acyl, acylperoxyl) free radicals, oxygen-containing structures (hydroperoxides, carbonyls, alcohols, carboxyls, lactones) and unsaturated groups (vinylic, vinylidene, allylic) are formed. Additionally crosslinked polymer chains formed by the radical recombination of lower-molecular-weight fragments can be found. Disproportionation and depolymerization result in low-molecular-weight products. Condensation polymers such as polyamides or polyesters lower their molecular weight by hydrolytic cleavage.

The concentration of the new structures (structural inhomogeneities) increases depending on the previous service time of the polymer and the previous application area (e.g., outdoor, high temperatures).

The generated oxygenated and/or olefinic structures are more sensible to further oxidation than the corresponding virgin polymer. Moreover, some of the oxygenated structures have thermoinitiating or photosensitizing effects. As a result, most recyclates are more sensitive than virgin polymers. Furthermore, recyclates containing these groups can enhance or initiate oxidation/photooxidation in blends with virgin materials or other polymers.

Besides the described structural inhomogeneities, recyclates contain impurities formed either through transformation products in trace concentrations or through foreign impurities which could not be removed by purification steps.

Stabilizers are consumed in protecting the polymer from oxidation. Often, the used phenolic antioxidants react, for instance, with hydroperoxide radicals and generate colored reaction products such as quinone methides, cyclohexadienones, and benzoquinones. After deactivation of hydroperoxides, phosphates are formed from phosphites. Salts and other transformation products arise from HAS (hindered amine stabilizers). Some of these transformation products still show some stabilizing activity, others, such as phosphates, are completely inactive. Nevertheless, some products can form polymer-insoluble precipitates influencing rheological properties and/or acting as nucleating agents in semicrystalline polymers. Generally, consumption of stabilizers results in insufficient protection of the recyclate for the second application.

Besides the transformation products of the original stabilization package, residues of polymerization catalysts are often present. It has to be mentioned that even in separated and so-called "single" polymers, catalyst mixtures influence their properties because of the often used different proprietary systems. It is well known that, for example, the catalyst systems used for the manufacture of HDPE not only result in different processing behaviour of the polymer but influence its degradation behaviour as well [4,5]. As a result, recyclates containing mixtures of polymers from different producers can be more problematic than single-grade polymers from one producer only.

Furthermore, other metallic impurities from contact media (e.g., rust) or from contaminated fillers will influence the stability. Copper ions and iron ions are known to catalyze homolysis of hydroperoxides and increase the consumption of phenolic antioxidants through their oxidation into cyclohexadienone compounds.

A further class of impurities consists of foreign substances. These materials could be inorganic or organic, e.g., flame retardants, printing inks, paint residues, surfactants and residues from contact media. Some of these substances are often harmful for the polymer because of their thermal instability and their degradation products reducing the mechanical properties and decreasing the stability of the recyclate. Macroscopic impurities (dust, metal parts, unmolten elastomers, etc.) should be removed for high-value applications in any case, for instance by melt filtration.

Finally, admixtures of foreign polymers can deteriorate completely the recyclate properties because most polymer mixtures are not compatible: mechanical properties but also processing and long-term properties will be extremely affected. For example, PVC impurities will degrade PET during processing and reduce thermal stability of polyolefins [6].

## CONCEPT FOR THE UPGRADING OF RECYCLATES

Usually a piece of used plastic cannot simply be reused in the form it was recovered. Rather, to some extent, in order to improve the quality of a recyclate, it has to be specifically sorted, separated, cleaned and reprocessed in optimized compounding steps. But in order to ensure that the recyclate is not considered merely as a surrogate, work has to be done to produce upgraded recyclates which can satisfy the requirements for the extended product life and appearance and adapt the recyclate to meet the requirements of the new application.

Fortunately, there is a complete range of additives for the formulation to various specifications available. Examples are compatibilizers, impact modifiers, stabilizers, reinforcement agents like glass fibres and mineral fillers as well as pigments used for repigmentation.

Restabilization is probably the most effective approach to improving the quality of any recyclate [6-11]. It is also one of the most effective techniques for increasing the substitution factor, fortifying the recyclate with the required properties and thereby achieving the ideal value of 1:1. As a result, the recyclate can substitute the virgin plastic in selected applications with a comparable performance.

### Closed-Loop Applications

Both virgin plastics and recyclates require stabilizers to protect against thermal and photo-oxidative degradation during processing. In addition to providing a good processing stability, stabilizers help retain physical and mechanical properties and provide an optimum protection against undesirable deterioration caused by light and heat helping a product to fulfil its task as long as required in any given environment. If it is intended that a recyclate is to substitute the virgin material in a given application, then, if nothing more, the amounts of stabilizers consumed in the first-life application have to be replaced.

As a rule, however, even this is not quite sufficient. The pre-damage combined with the changes in the molecular structure together with the influence of plastic mixtures reduce the thermal and photo-oxidative stability of the recyclate. As a result, restabilization is often necessary to cope with these negative interactions.

Some examples of closed-loop applications should show the capabilities of well-adjusted restabilization.

### Polypropylene Battery Case Recyclate

Although the recovery and recycling of old battery cases has been known for some time, in Europe the highest portion of this recyclate is still used for applications not requiring any essential plastic quality. High-grade application fields require a complex processing technology and low concentrations of lead and sulfuric acid residues as well as a careful reformulation. By adding a single stabilizer system (Recyclostab 451), which is much more effective than the stabilizers normally used for virgin material, the most crucial processing handicaps, the stability of the plastic during processing and poor long-term thermal stability, can be compensated [6]. For example, compared with a non-stabilized recyclate or a recyclate stabilized with conventional stabilizers (e.g. Irganox B 215), an excellent long-term stability is seen in the bending test until embrittlement at 135 °C (Fig. 1).

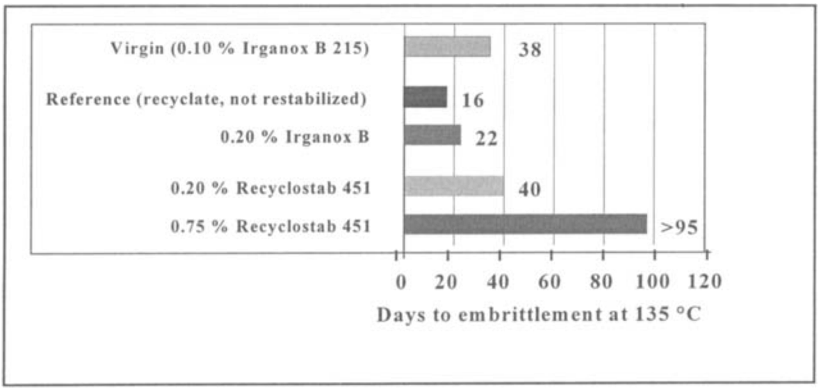



Fig. 1: Long-term thermal stability of PP scrap from battery cases (extrusion: twin screw, max. 260 °C, 100 rpm; test samples: 2 mm, injection-molded)

Even an addition of twice the quantity of the stabilizers normally used for the virgin material will not meet specific product stabilization requirements. By adding Recyclostab 451 to a recyclate in sufficient quantities, however, it is possible to prolong the potential life-span of a product matching the virgin material. Extensive research has proved that the Recyclostab 451 recyclate stabilizer provides outstanding protection during the processing and end use of all recyclate from the battery-case material tested regardless of the processing technique used or the region the battery cases originally came from.

## Low-density Polyethylene Film Recyclate

The LDPE virgin material for use as films for food packaging, bags, etc. is normally intended for use in short-life product applications only and, therefore, usually contains very little stabilizer and, in some cases, is not even stabilized at all. Processing LDPE recyclate with an inadequate stabilizer content produces a diminished MFR (melt flow rate), crosslinking, discoloration (yellowing) and a decreased output as well as varying physical and mechanical properties. The LDPE recyclate, therefore, can only be used for making relatively thick films in contrast to the virgin material. This, however, is not quite ecologically sensible as it does not lead to any saving of resources and contradicts the "less is more" message which argues that plastics excel at using less to do more (substitution factor !). An addition of a stabilizer specially designed for the LDPE film recyclate (Recyclostab 421) produces the following effects [12].

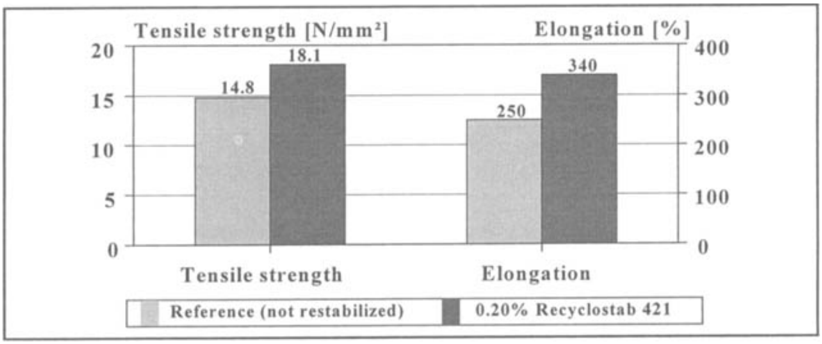



Fig. 2: Mechanical properties of LDPE recyclate (extrusion: single screw, max. 220 °C, 30 rpm; test samples: 30-µm blow-molded film; tensile strength, elongation: DIN 53455)

The rheological behaviour is modified and, consequently, improvement of physical and mechanical properties such as elongation, tensile strength and flexibility (Fig. 2) as well as tear strength and dart drop impact is observed. As a result, it is possible to manufacture films of reduced thickness while maintaining required properties. Moreover, in blends of the recyclate/virgin material, the proportion of the recyclate can be substantially increased.

Additionally, it is frequently possible to perceive a reduction in odor formation when stabilizers are added prior to the film manufacture [13]. There is a simple explanation of this effect: The stabilizers impede the decomposition of the polymer thus preventing the formation of low-molecular-weight volatile by-products.

## Acrylonitrile-Butadiene-Styrene from Automotive Parts

ABS is used for housings of electrical/electro equipments, for leisure articles and for automotive parts because of its impact strength, scratch resistance, dimensional stability and minor sensitivity to temperature changes. A modern car with up to 160 kg of plastics [14] contains approximately 10 % of ABS [15], e.g., radiator grills and interior panels. For that reason, the automotive industry is one of the main consumers of ABS in Western Europe.

A most important criterion for the useful recycling of ABS is the maintenance of impact strength during the service period. An accelerated heat aging of the recycled interior automotive parts shows that the loss in mechanical properties can be significantly reduced by restabilization. Without a stabilizer addition, 30 % of the initial Izod impact strength is lost within 1000 h at 80 °C in comparison with less than 10 % when 0.25 % of Recyclostab 451 is added (Fig. 3).

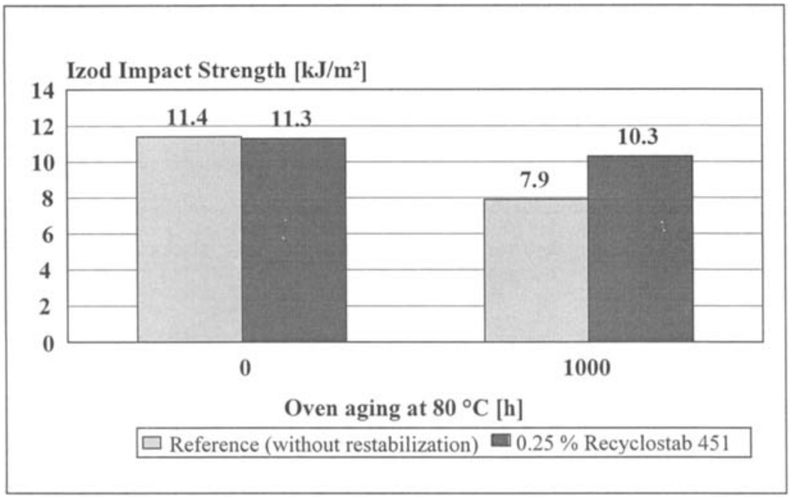



Fig. 3: Mechanical properties of ABS recyclate

## High-Density Polyethylene Waste Bins

Waste bins manufactured usually from HDPE are a source of a single material which is available everywhere. Therefore, it has to be taken into consideration to recycle this high-value HDPE in a closed loop. All products from outdoor applications intended to reuse require an adjusted restabilization according to the active stabilizer residues. Not only processing and long-term heat stability are decisive but, above all, the light stability.

Natural weathering tests clearly show that without restabilization, a detrimental decrease in mechanical properties can be expected within a very short time. The radiation of 240 kLy, as shown in Fig. 4, corresponds to 2-3 years of natural weathering in central Europe. The measured property (tensile impact strength) is the criterion laid down in the German quality standard RAL.

Addition of Recyclossorb 550, a stabilizer system consisting of basic stabilization in combination with HAS (hindered amine stabilizer) compounds prevents degradation. The reuse of the recyclate from waste bins in new ones seems to be feasible. Restabilization offers the opportunity to fulfil existing standards and to achieve the originally present level of quality.

The results shown have been confirmed by a joint project carried out at the Süddeutsches Kunststoffzentrum (SKZ) with tests of oxidation stability, mechanical properties and artificial weathering of the recyclate from waste bins: The restabilized recyclate from the used waste bins attains the RAL standard [16]. Furthermore, it was proved that the restabilized recyclate definitely surpasses blends of the stabilized virgin material and used plastics.

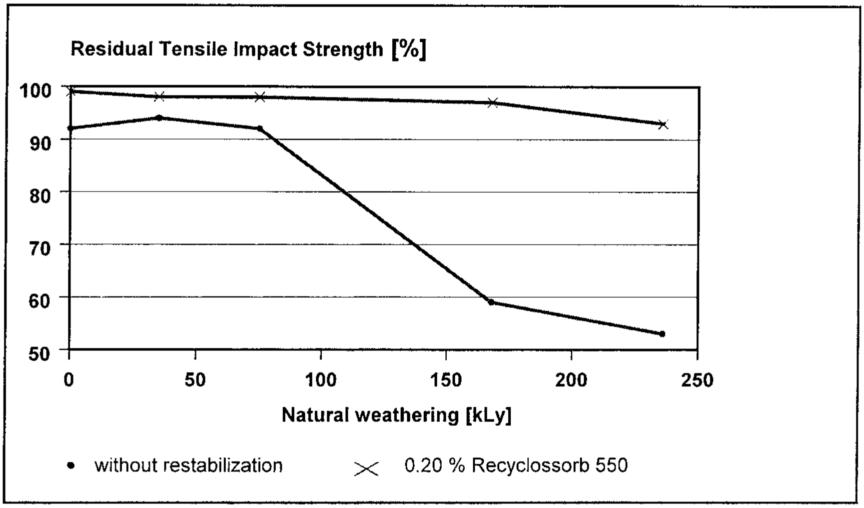



Fig. 4: Light stability of the HDPE recyclate from waste bins (recyclate: carbon-black-pigmented, 2-mm injection-molded plaques; weathering: South Africa, 45° North, 160 kLy (1 year, starting June))

## Recyclates from Short-term to Long-term Applications

The plastics that were originally used in short-term applications, such as for food packaging, definitely do not contain enough residual stabilizers and contain virtually no light stabilizers. Consequently, such a recyclate is not durable enough to be used in any long-term application. Furthermore, formulation components introduced for color reasons such as carbon black or for improving mechanical properties such as compatibilizers can influence the long-term stability of the recyclate.

## Polyethylene/Polypropylene Bottle Fraction for HDPE Applications

The HDPE virgin material can be purposefully stabilized to any required specifications [4,5]. There are, furthermore, several well-known solutions to the optimum restabilization of various types of the single HDPE recyclate regardless of the manufacturing technology. An extremely challenging problem, however, is the stabilization of mixed polyolefins. Experiments recently carried out on a bottle fraction, which, for the most part, consisted of HDPE with caps made from PP, have shown that conventional stabilizers such as Irganox B 225 do not lead to any substantial improvement. Our asumption is that the specific behaviour of the blend is regulated mainly by the relatively low concentration of PP.

Figure 5 demonstrates how, using the Recyclostab 451, it was possible to maintain an absolutely constant MFR during multiple processing phases.

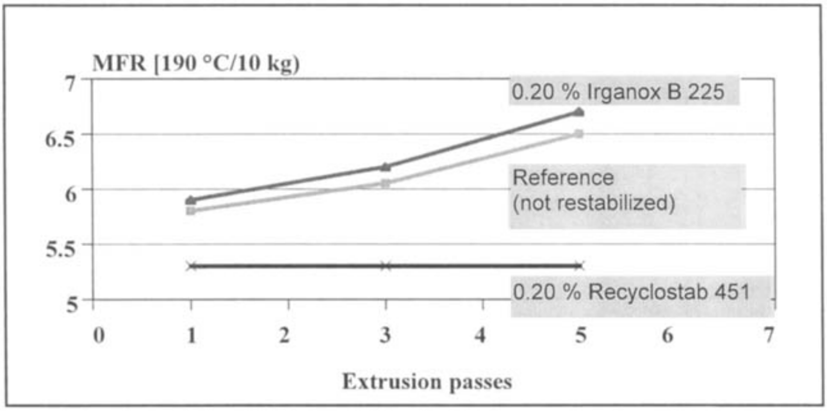



Fig. 5: Processing stability of polyolefin blends from bottles (PE/PP = 95/5) (extrusion: twin screw, max. 240 °C, 100 rpm. MFR: ISO 1133, 190 °C/10 kg)

Even more significant is the influence of Recyclostab 451 on the long-term thermal stability. HDPE containing only small quantities of stabilizer can, with regard to oven ageing, be considered to be relatively stable; PP, on the other hand, can only be used for long-term applications when it is well fortified with stabilizers. During the compounding and processing test procedure with mixed polyolefin bottles, we found that without sufficient stabilization, the test sample failed very rapidly. In a typical standard 120 °C thermal test, the test sample survived only 18 days (in the case of 100 % HDPE recyclate without restabilization this was 73 days), which means that the material cannot be realistically used in typical HDPE applications (Table 1).

Table 1: Long-term thermal stability of HDPE in comparison with HDPE/PP blend

| Polymer | Days to embrittlement at 120 °C | |
|---|---|---|
| | 1st extrusion pass | 5th |
| **HDPE virgin** | | |
| not stabilized | 5 | 2 |
| + 0.20 % Irganox B 215 | 131 | 55 |
| + 0.20 % Irganox B 225 | 156 | - |
| **HDPE recyclate** | | |
| not restabilized | 73 | – |
| + 0.20 % Recyclostab | 144 | – |
| **95 % HDPE/5 % PP recyclate** | | |
| not restabilized | 18 | 14 |
| + 0.20 % Irganox B 225 | 37 | 25 |
| + 0.20 % Recyclostab 451 | 116 | 115 |

An addition of as little as 0.2 % Recyclostab 451 increases this period to the ideal 100-day level again, i.e., the survival period normally expected of the virgin material. It is, furthermore, interesting to note that whether the material is extruded once or five times makes no longer any difference. This is a further evidence of the protection against degradation the recyclate stabilizer provides especially during processing.

Increasing amounts of PP (or impurities such as PVC) result in further lowering of the stability [6]. Increased amounts of stabilizers are required in this case.

If the recyclate, like in the above mentioned bottle fraction, is intended for the outdoor use and if it is to fulfil its task as long as possible, then weatherability is also a decisive factor, more important than pure durability. In this case, therefore, the stabilizer system applied must contain effective light stabilizers, for example, HAS. Lucrative, effective and easy to apply are stabilizer packages such as Recyclossorb 550 which contain not only the components required for the basic stabilization but also stabilizers which have proved to be very effective in solving the problems associated with the light exposure.

## Recyclates Containing Carbon Black

Besides the impurities and inhomogeneities of the recyclate introduced, the impact of formulation components on the properties has to be considered. For example, carbon black is often used to homogenize different colors or to improve light stability. On the other hand, the negative effect of carbon black on the thermal stability is well known [17-20]. This effect is particularly apparent in recyclates from mixed polyolefins. It is necessary to boost the thermal stabilization package in order to compensate for any reduction in properties caused by high concentrations of carbon black.

Figure 6 illustrates how a recyclate stabilizer such as Recyclostab 451 used in combination with a polymeric HAS compound such as Chimassorb 944 or Tinuvin 783 can provide maximum thermal stability. For the effective light stabilization of mixed polyolefins and HDPE recyclates, blends of polymeric HAS compounds such as Tinuvin 783 or the above mentioned Recyclossorb 550 are recommended. Moreover, an additional cost-effective advantage is gained due to the synergic effect of these HAS blends.

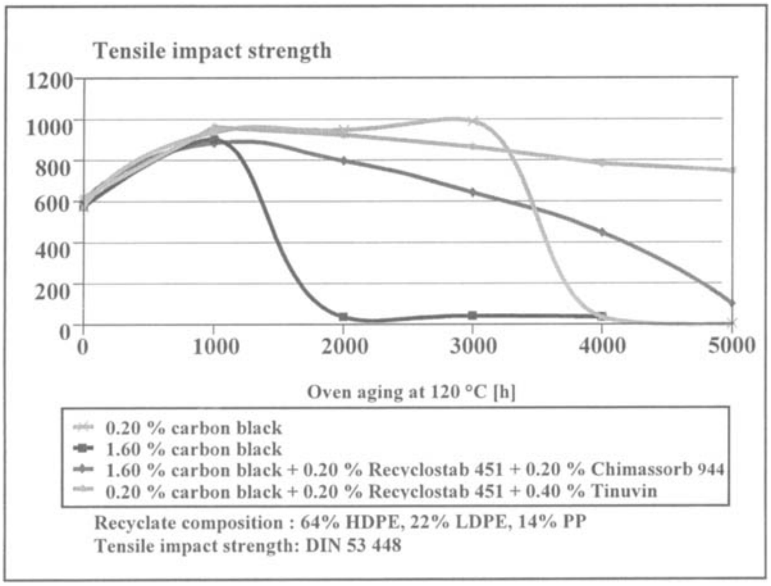



Fig. 6: Influence of carbon black on long-term thermal stability of polyolefin recyclates

In our experience, light and thermal stabilizers used in combination with low concentrations of carbon black for pigmenting have proved to be several times more effective in terms of cost and performance, at least in most recyclate applications, than merely an addition of carbon black alone. Furthermore, the negative effect of thermal oxidation caused by carbon black can be maintained at a non-critical level.

## Polyethylene/Polyamide Film Recovery in Outdoor Applications

PE/PA coextruded film used in food packaging is a very common form of plastic waste [21,22]. These films cannot be separated by conventional methods. Consequently, new applications for this recyclate will have to be found. A plastic blend, which is suitable for injection molding and extrusion, can be produced by adding compatibilizers. Artificial weathering tests, however, quickly show the limitations of such a blend. The samples did not survive very long. The ultimate total loss of all physical and mechanical properties was very rapid. An addition of a HAS compound used in combination with selected antioxidants can increase the performance in terms of light stability, but still the result is not quite satisfactory [7].

Figure 7 illustrates how the required innovation in the formulation used was provided by adding zinc oxide. The recyclate samples tested (with an acrylic compatibilizer) still maintained most of their initial mechanical properties even after 8000 hours of artificial weathering tests.

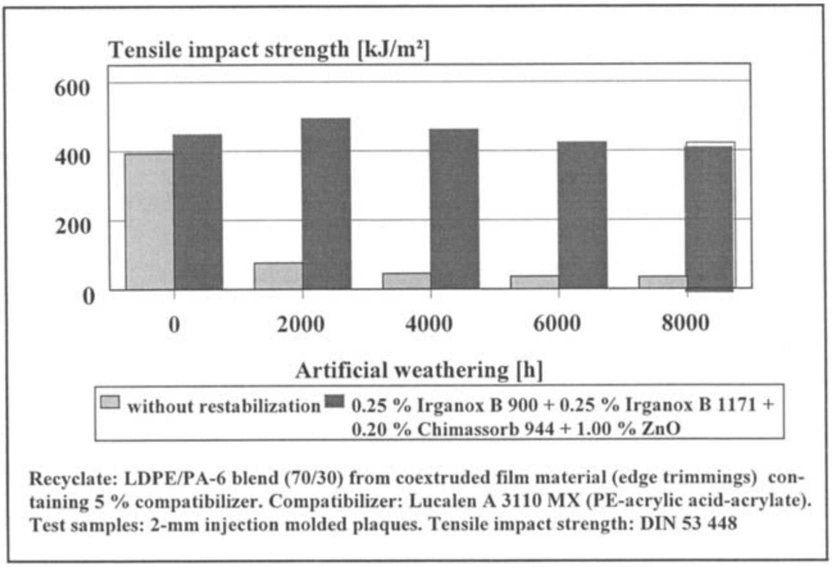



Fig. 7: Light stability of a compatibilized LDPE/PA-6 blend

## Minimizing Damaging Effects of Impurities

A balanced combination of processing, thermal and light stabilizers can significantly improve the stability of a recyclate preventing the loss of physical and mechanical properties as well as providing the best protection of surface-aesthetic properties. However, even a formulation which has been carefully optimized can still frequently not be enough to meet the product specific property requirements for some predamaged recyclates or when the recyclate contains impurities which are particularly unacceptable. For certain types of recyclate, improvement of the properties can be achieved by an addition of reactive compounds. These additives react directly with impurities and, by a chemical reaction or complex formation, produce a desensitizing effect.

## Polypropylene/EPDM Recyclate Containing Paint Residues

The paint residues in a PP/EPDM recyclate from used car bumpers can strongly influence its mechanical properties and particularly the long-term heat stability. A new combination of stabilizers containing a reactive additive can compensate the negative influence of the paint residues.

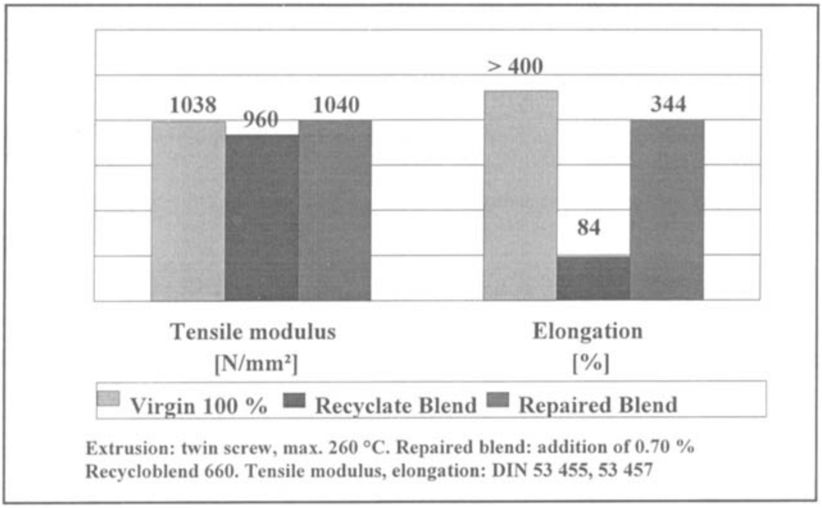



Fig. 8: Mechanical properties of repaired PP/EPDM blend (virgin/painted post-used material 50/50)

Figure 8 demonstrates how critical physical and mechanical properties such as elongation can be raised to the same level as that of the virgin material while maintaining the tensile modules.

Furthermore, long-term heat stability as well as physical and mechanical properties can be considerably maintained during the aging process so that here once again, we have a recyclate which can seriously compete and in some cases even outperform the virgin material [6].

## Repair of Polycondensates

Engineering plastics such as polyamides and polyesters manufactured by polycondensation are primarily sensitive to hydrolytic degradation during use. The consequences are a reduction in the molecular weight and a loss of physical and mechanical properties. In more demanding processes and applications, these losses have to be compensated for. One such method is the solid state polycondensation [23,24]. However, the use of the reactive extrusion technique provides a better cost performance.

## Molecular Weight Build-up in Polyamides

By adding a combination of a reactive additive and an additive, which has a catalytic effect (development product EB 36-50), to a hydrolytically predamaged polyamide, it can attain its initial molecular weight and, consequently, all mechanical properties.

Chemically regarded, the reactive additive is a selected bifunctional oxirane compound. The catalytically active additive accelerates the reaction in such a way that the process is feasible in extrusion conditions. Moreover, the additive is effective in providing processing stability while maintaining good long-term heat stability.

Careful adjustment of the concentration of various components provides the basis for manufacturing tailor-made products. Figure 9 clearly demonstrates the decrease in the melt flow rate (increase in molecular weight) as a function of EB 36-50 concentration.

Figure 10 illustrates how the polyamide 66 production waste from injection molding can be transformed into a material suitable for extrusion.

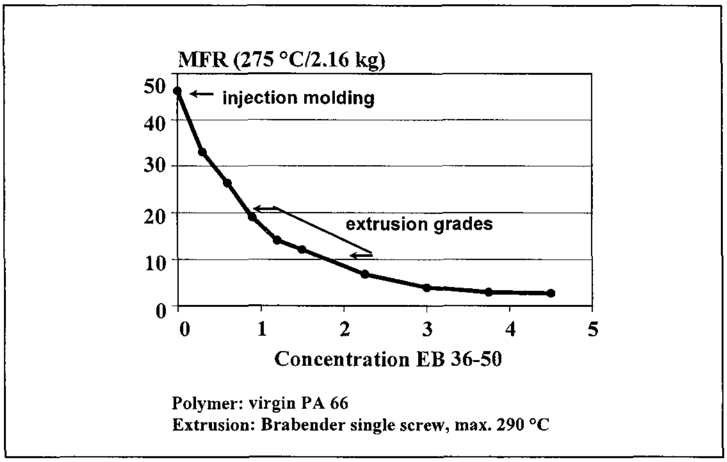



Fig. 9: Tailor-made molecular weight (melt flow rate decrease) of polyamide 66

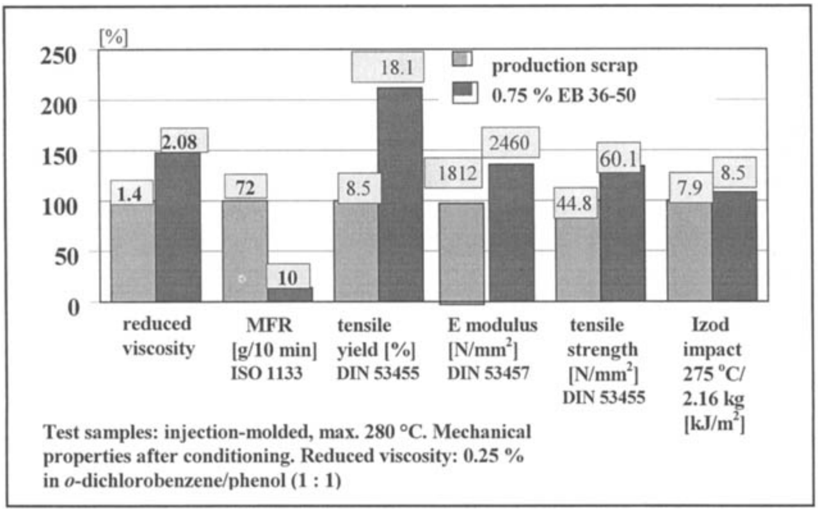



Fig. 10: Molecular weight build-up of the polyamide 66 production scrap

## Modifying Recyclate from Engineering Blends

Provided appropriate adjustments are made, products designed to build up molecular weight are also suitable for modifying PBT/PC blends recyclate, meeting, as a result, specific virgin material stabilization requirements [25]. When manufacturing automobile parts such as bumpers, the PBT/PC blend undergoes a breakdown in molecular weight as well as an increase in the MFR. Subsequent processing steps such as recycling increase the material damage further. The material is, consequently, no longer suitable for an equivalent application.

The use of Recycloblend 660 lowers the MFR value (e.g. from 13.8 to 9.5 at an additive content 0.7 %, measured at 260 °C/2.16 kg). Combined with a cleaning process, the specifications stipulated for the virgin material can be attained even in the case of this complex blend system (transesterification, changes in the morphology). This is done by increasing the elongation (Fig. 11) while maintaining the tensile strength (virgin ~40.7 N/mm², restabilized recyclate 41.9 N/mm²). Additionally, the blend containing repair compounds can be processed under standard conditions.

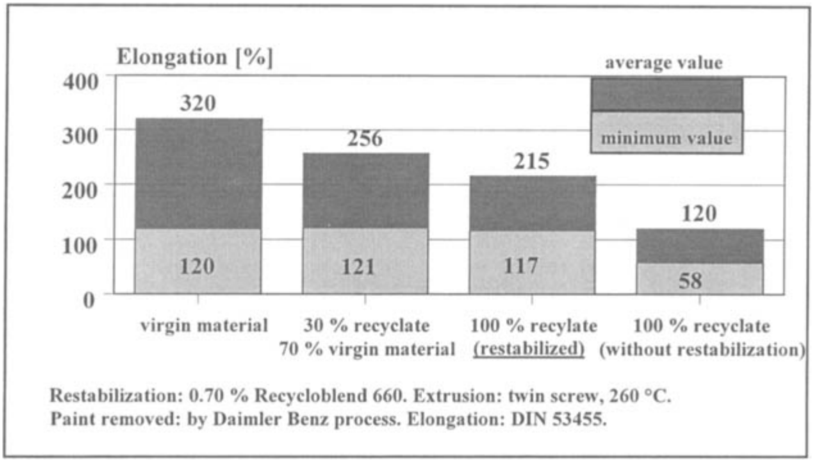



Fig. 11: Influence of repair compounds on elongation of the PBT/PC recyclate from bumpers

## HIGH-VALUE RECYCLATES USING THE CONCEPT OF RESTABILIZATION AND REPAIR COMPOUNDS

Both selected additives used for the development of virgin plastics and additives specially designed for recycled plastics contribute to a successful recycling of used plastics and production scrap. Currently, there exists recycling of plastics in a closed-loop system which embraces products like bottle crates, waste bins, containers, all kinds of plastic films, automotive parts and bottles. Furthermore, there are numerous examples of the high-grade use of recyclates and even recyclates made from packaging materials, for instance, in non-pressure drainage and cable ducts as well as pallets.

The concept of restabilization and repair compounds enables the high-value reuse of recyclates and brings about a substantial increase in the substitution factor. The recyclate, as a result, can be used to replace virgin material in many applications. The restabilized recyclate not only matches the virgin material in terms of performance, but also has an additional ecological advantage.

## REFERENCES


[1] APME Technical & Environmental Centre, Brussels: Information System on Plastics Waste Management in Western Europe - European Overview, 1995 Data, February 1997

[2] N.N.: "Eco Balance" for Recycling of Plastics Packaging, PIE, October 15, 1995, p. 7

[3] Pospisil, J., Sitek, F.A., Pfaendner, R.: Upgrading of Recycled Plastics by Restabilisation - An Overview. *Polym. Degrad. Stab.* 48, 1995, 351-358

[4] Moss, S., Zweifel, H.: Degradation of Stabilization of High Density Polyethylene during Multiple Extrusions. *Polym. Degrad. Stab.* 25, 1989, 217-245

[5] King, R.E., Kuell, Ch.: Potential Impact of Catalyst Residues on Polyolefin Stabilization. Presented at 17th Annual Int. Conf. *Advances in Stabilization and Degradation of Polymers*, Luzern 1995, p. 145-65

[6] Pfaendner, R., Herbst, H., Hoffmann, K.: Recent Developments in Restabilization of Recyclates - The Solution for High Value Applications. *Eng. Plast.* 9, 1996, 249-281

[7] Pfaendner, R., Herbst, H., Hoffmann, K., Sitek, F.: Recycling and Restabilization of Polymers for High Quality Applications. An Overview, *Angew. Makromol. Chem.* 232, 1995, 193-227

[8] Conference *Recyclate durch Additive erfolgreich aufwerten.* Süddeutsches Kunststoffzentrum, June 11-12, 1996, Stuttgart

[9] Herbst, H., Capocci, G.: Automotive Plastics Recycling - Closed Loops by Restabilization. Presented at *TPO's in Automotive*, October 28-30, 1996, Novi, MI, USA

[10] Herbst, H., Hoffmann, K., Pfaendner, R.: Durable Goods from Recyclates for Outdoor Applications - The Role of Light Stabilizers. Presented at *R'97 Congress*, February 4-7, 1997, Geneva, Switzerland, p. 1116 - 1121

[11] Pfaendner, R.: Perspektiven zum werkstofflichen Kunststoff-Recycling - Mit Additiven die Marktchancen von Recyclaten verbessern. Presented at colloquium *Werkstoffliche Verwertung thermoplastischer Kunststoffe*, February 4, 1997, Aachen, p. 8.1-8.31

[12] Pfaendner, R., Herbst, H., Hoffmann, K.: Probleme beim werkstofflichen Recycling meistern: die Basisstabilisierung. *Plastverarbeiter* 46(8), 1995, 36-42

[13] Kessler, A.: Geruchsminderung an Rezyklaten aus Polyolefinabfällen. Technical Paper, Universität-Gesamthochschule Kassel, Institut für Werkstofftechnik, Entwicklungsgesellschaft für die Wiederverwertung von Kunststoffen mbH (EWvK)

[14] Graser, K., Hoock, R.: Rezyklate im Fahrzeugbau. *Kunststoffe* 85, 1995, 3, 330-335

[15] Weber, A.: Plastics in Automotive Engineering and Aspects of Plastics Waste from Abandoned Vehicles. *Plast. Rubber Compos. Process. Appl.* 16, 1991, 143-156

[16] Fuchs, S.: Müllgroßbehälter aus Regranulat? *Plastverarbeiter* 47(1), 1996, 48

[17] Pfaendner, R., Herbst, H., Hoffmann, K., Klingert, B., Sitek, F., Cooper, T.: Lebensdauer von rezyklathaltigen Formteilen erhöhen. *Kunststoffe* 85, 1995, 81-84

[18] Rotschova, J., Pospisil, J.: Influence of the Carbon Black Chezacarb EC on Polyolefin Thermooxidation: A Model Study with Cyclohexene Doped with Chain-breaking Antioxidants, *Makromol. Chem.* 194, 1992, 201-211

[19] Mwila, J., Miraftab, M., Horrocks, A.R.: Effect of Carbon Black on the Oxidation of Polyolefins - An overview. *Polym. Degrad. Stab.* 44, 1994, 351-356

[20] Rysavy, D., Tkadleckova, H.: Thermooxidative Stabilität von gefülltem Polypropylen. *Plaste Kautsch.* 38, 1991, 273-275

[21] Grützner, R.-E., Gärtner, R., Hock, H.-G.: PE-PA-Verbundfolienreste - Eigenschaften und Grenzen der Verwertbarkeit. *Kunststoffe* 83, 1993, 369-372

[22] Hausmann, K.: Verbundfolien wiederverwerten mit Verträglichkeitsvermittlern. *Kunststoffe* 85, 1995, 446-451

[23] Steiner, U.B., Borer, C., Oertli, A., Pfaendner , R.: Solid State Polycondensation of Recycled Polyethylene Terephthalate (PET). Presented at *R'97 Congress*, February 4-7, 1997, Geneva, Switzerland, p. 1126-1131

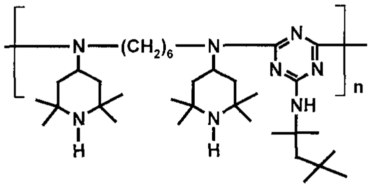
[24] Herbst, H., Hoffmann, K., Pfaendner, R.: New Opportunities for PCR by Restabilization. Presented at *ARC '95*, 2nd Annual Recycling Conference, Akron (Ohio), USA, Nov. 2-3, 1995, p. 17-33

[25] Hoffmann, K., Herbst, H., Pfaendner, R.: Stabilizers Improve the Quality of Used Plastic Automobile Components. Presented at *Plastics in Automotive Engineering*, VDI, Mannheim 1996, p. 213-227

## Appendix

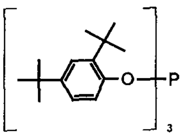
### CHIMASSORB 944

poly({6-[(1,1,3,3-tetramethylbutyl)amino]-1,3,5-triazine-2,4-diyl}[(2,2,6,6-tetramethyl-4-piperidyl)imino] hexane-1,6-diyl[(2,2,6,6-tetramethyl-4-piperidyl)imino])



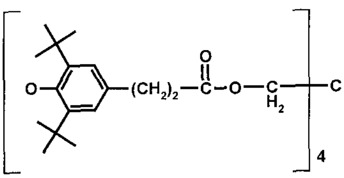
### IRGAFOS 168

tris(2,4-di-*tert*-butylphenyl) phosphite



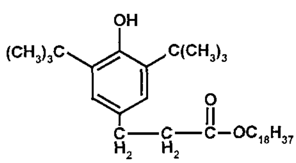
### IRGANOX 1010

pentaerythritol tetrakis[3-(3,5-di-*tert*-butyl-4-hydroxyphenyl)propionate]



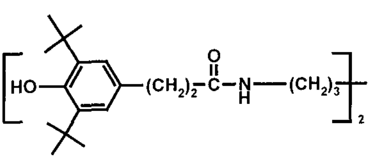
### IRGANOX 1076

octadecyl 3-(3,5-di-*tert*-butyl-4-hydroxyphenyl)propionate



### IRGANOX 1098

*N,N'*-(hexane-1,6-diyl)bis[3-(3,5-di-*tert*-butyl-4-hydroxyphenyl)propionamide]



IRGANOX B 215 (2:1 blend Irgafos 168 - Irganox 1010)

IRGANOX B 225 (1:1 blend Irgafos 168 - Irganox 1010)

IRGANOX B 900 (4:1 blend Irgafos 168 - Irganox 1076)

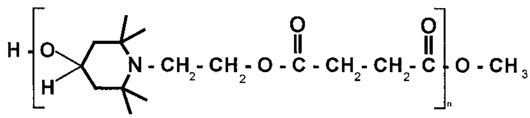
IRGANOX B 1171 (1:1 blend Irgafos 168 - Irganox 1098)

RECYCLOSTAB 411
RECYCLOSTAB 421 (contain antioxidants and costabilizers)
RECYCLOSTAB 451

RECYCLOSSORB 550 (contains antioxidants, costabilizers and HAS light stabilizers)

RECYCLOBLEND 660 (contain repair compounds)
EB 36-50

TINUVIN 622 poly[2-(4-hydroxy-2,2,6,6-tetramethyl-1-piperidyl)ethyl hydrogen succinate]



TINUVIN 783 (1:1 blend Tinuvin 622 - Chimassorb 944 )