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Additives for Mechanical Plastics Recycling—Need for Action by the Legislator

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Abstract: In recent years, a market for chemical additives to improve the quality of plastic recyclates has been established. High growth opportunities are expected for these additives. The products are very diverse and can be used, for example, for the post-stabilization of recyclates or to reduce unpleasant odors. There are also products on the market that can repair damaged polymers. And additives are available that improve the miscibility of inhomogeneous sorting fractions. On behalf of a plastics recycler, the authors have attempted to find out the chemical identity and frame formulation of these plastic additives. However, this information is mostly not disclosed. Even in the available safety data sheets, the composition of these products was regularly not included. Only in individual cases, individual substances which are subject to declaration (REACH/CLP) have been specified. However, it is known from discussions and the literature that highly reactive substances are sometimes used for these products, which are to be added directly to the hot melt in the extruder. Now that the SME recycling industry is already confronted with plastic waste containing banned additives from the past (risk cycle, legacy chemicals), a new problem is emerging for the future: are these additives sufficiently safe? The authors advise caution here and therefore at least against the use of recycling additives whose chemical identity and frame formulation are not disclosed. This can lead to the 'recycling privilege' under REACH no longer applying to plastic recyclates, with serious consequences for recyclers. Scientific studies should also be carried out to determine whether these recycled additives pose any risks to consumers.

Keywords: recycling additives; substances of concern; 'risk cycle'; eco-design; digital product passport; frame formulation; End-of-waste (EoW) status; 'recycling privilege'

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1. Introduction

Mechanical recycling uses recyclates from discarded (End-of-Life, EoL) plastic products. Recyclate (plastic recyclate) is a generic term. This includes [1]:

- Regrind: is obtained by grinding plastic
- Regranulate: is obtained as granulate from regrind via a melting process.
- Regenerate: is obtained via a melting process (compounding) with the addition of additives to improve properties.

Plastic products are compounds of one or more types of polymers and additives. "Additives are essential to making thermoplastics processable and to improving end-use properties" [2]. Depending on the application, the share of additives in a plastic compound can have a few percentages and can reach more than 50 weight-% (wt.%) in individual cases [3]. These additives can also include substances that are no longer permitted as additives today. This leads to recyclates which, strictly speaking, should no longer be permissible [3,4]. This problem is known under the terms "chemical legacies" and "risk cycle" [5,6]. A solution to this conflict of objectives between increasing recycling and ensuring health protection is not yet in sight. There is hope that at least packaging plastics will be less affected and that the additives in the highly specialized plastics in the WEEE and construction sectors will become less problematic over cycles and time.

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The basic idea of circular economy is based on many, perhaps even perpetual cycles and is therefore a better concept than the linear economy that dominates today. Technical literature on plastics provides extensive findings on the stability of polymer molecules. These are long, chain-like molecules consisting of identical structural units (“monomers”) that are chemically bonded together. Although polymer molecules behave differently depending on the type and number of monomers, altogether they are a rather fragile structure. In view of the general experience of the longevity and stability of various everyday plastic products, this fact is hardly known. This also applies to the fact that the existing stability is usually not primarily due to the polymer molecule, but to chemical additives that protect and modify the polymer molecule.

The first conversion of virgin plastic granulates into a product requires melting (heat) and the exertion of mechanical forces. This process alone severely damages the polymer molecule and, depending on the type of polymer, can even lead to chain reactions (PVC, for example). For this reason, special protective additives must be added during the initial melting process in order to minimize possible damage. However, these so-called stabilizers are used up proportionally during the process. Depending on the amount added, there may not be enough stabilizers left for a second melting during recycling. "Nevertheless, good, basic stabilization of the virgin material is one prerequisite for a qualitatively high level recycling […]. On the other hand, restabilization before each recycling step is favored while 'over'-stabilization at the first processing can cause problems" [7], p. 999–1000].

The described sensitivity of the polymer molecule is chemically complex and can exhibit very different reactions. These all have in common that changes occur in the polymer molecule (shortening, linking, chemical changes), which in consequence would change the mechanical properties of the plastic. It is therefore necessary to protect the polymer molecule not only for the initial melting, but also for the subsequent use phase. For the latter, other substances are often required than for melting, especially if the plastic products have a longer service life or are exposed to sunlight or weather conditions (heat, moisture).

The need to protect the polymer molecule can often reach so far that the stabilizers require their own additives to enhance their effect or protect them from chemical or biological attack. Stabilization is therefore a complex chemical concept that includes various substances of different concentrations and is very strongly composed for the different kind of polymers and the possibilities of the use phase. Other additives are added for various other reasons, e.g. to improve the properties of the finished plastic product (flame retardants, pigments, plasticizers, surface protection, etc. [3,7]).

Stabilizers for melting, but also for the use phase, chemically decrease in the concentration in the plastic, as they are converted or degraded into other substances and are therefore no longer available to protect the polymer. This degradation can reach a complete consumption of the stabilizers (concentration zero). EoL-plastics then enter the recycling process virtually unprotected. However, EoL-plastics usually still contain a certain grade of residual stabilization, although the composition and quantity of the remaining active stabilizers are generally unknown.

Despite stabilization, EoL-plastics enter the first recycling loop already damaged. This damage will certainly increase with each subsequent loop, although there is still insufficient experience of the extent of the damage. Irrespective of, but parallel to, the expected gain in knowledge over the next few years, the regulatory requirements for mechanical recycling will increase significantly. One of the reasons for this is the stricter regulations introduced for various sectors at European level (single-use plastic products [8], packaging [9], vehicles [10]), according to which virgin plastic in new products must be proportionately replaced by recyclates (substitution). These quotas are ambitious, starting for the year 2030 and continuing to increase in the years thereafter.

To meet this challenge, the chemical industry has developed a whole market for additives to improve the quality of recyclates [7,11,12]. The aim of our research, commissioned by a plastics recycler, was to investigate the potential performance of these additives and whether their use can be recommended. The first results of this research have been published in a German journal [13]. We are hereby publishing these findings in order to highlight the need for action.

2. Materials and Methods

The first step of the investigation consisted of a desktop/internet search followed by direct contact with suppliers to obtain technical data sheets and safety data sheets (SDS) for the recycling additives on offer. Subsequently, inquiries were made to the respective contact persons of the suppliers for further clarification of the identity of the active ingredients and the frame formulation.

3. Results

Mandatory disclosure of the frame formula has been established practice for years in other application areas such as detergents—see Regulation (EC) 648/2004, Annex VII [14]. We deliberately mention here the practice that has been established for decades in the detergent sector because this practice can serve as a model for recycling additives.

With regard to the recycling additives which we have investigated further, however, it was not possible to determine a frame formulation in any case. Technical data sheets and SDS were made available either on the Internet or on request. However, the information provided was usually completely inadequate. For example, there was information such as "plastic additives", "organic components", "mixture" or "polymers", but no information on which ingredients are contained in the products. Only in the few cases where the active ingredients were undoubtedly subject to declaration—for example CaO, because it is corrosive—was the identity of the active ingredients disclosed. However, even here it was often not possible to determine any further information in the sense of a frame formulation.

Personal inquiries to the company representatives provided additional information, but, in the end, no one was willing to clarify the frame formulation. Reference was regularly made to the necessary confidentiality of trade secrets and confidence was requested that the ingredients had been tested by the company and were safe.

Table 1 shows a selection of the recycling additives available on the market, broken down by manufacturer. We have refrained from marking the products for which no information on the substance composition was provided, as we do not want to brand any company. However, the non-disclosure applies to the vast majority of additives listed in Table 1. We are happy to pass on our detailed knowledge of individual products bilaterally on request.

Table 1. Selection of some common recycling additives available on the market (as of 12/2024).

Provider	Program series	Relevant single products and master batches
ADEKA Polymer Additives	Cycloaid	UPR-001P, UPR-011P, UPR001X, UPR-11P, UPR-011X, UPR-021
Baerlocher	Baeropol	T-Blend
BASF	IrgaCycle	PS 030 G, PS 031 G, PS 032 G, UV 033 DD, XT 034 DD
Brüggemann	Bruggolen	P30, P31, P32, P 33, M 12, M 125 1, M 125, M 141 7, M 1253, M 1417, R 8895, TP R2090, TP-R2162
Brüggemann	Compolin	CO, UL 07,
BYK	RECYCLOBYK	4370, 4371, 4372, 4373, 4376, 4374, 4375,
BYK	Scona	TPPE 2400, TPPE 5002
Dover Chemicals	Doverphos	LPG-12
Dow Du Pont	Fusabond	P 353, P 613, E 226,
Dow Du Pont	Elvaloy	AC 1224, AC 3217, PTW, E 226,
Evonik	Tego	XP 21024, XP 21025
ExonMobil	Vistamaxx	130, 3000, 3020 MED, 3980 FL, 3588 MED, 6000, 6102, 6202 MED, 6502, 6902, 7020v BF, 7050 BF, 8380, 8580, 8880, 8580
Kraton Polymers	Circular	3000
Lanxess	Stabaxol	3020 MED

Provider	Program series	Relevant single products and master batches
Nexam Chemicals	Nexamite	R201, R202, R203, R305, A94, A99, M 992007, M021200, M991500, M992000, 3980 FL
Nordic Crafting Company	Acti-Tech	3588 MED
Raschig		6000
SI Group	Evercycle	LD-101 S, LD-104 P, PET-102D, PET-103 D, PP-101 S, LD-1015, LD-6102
Songwon	Sognox	6202 MED
The Compound Company	Exelor, Yparex, EcoForte	6502
Ventellus Specialities	ZeMac	6902, 7050, 8380, 8580, 8880

4. Discussion

The performance profiles of the recycling additives are known from the specialist literature, and individual active substances are also mentioned. The available information and open questions on the main groups of recycling additives are presented below.

4.1. Stabilizers

To stabilize the respective types of plastic (initially for processing and later for the use phase), active substances similar to those used for virgin plastics are used as recycling additives. As with virgin plastics, at least two, if not more, active ingredients are regularly used in different concentrations. These formulations consist of antioxidants, protective additives for processing / plastification and co-stabilizers, and may also contain light stabilizers. In particular, defined phenols and phosphites are used as active ingredients. More than a dozen different active ingredients are commonly used. The stabilizing formulations for virgin plastics are polymer-specific. In contrast to stabilizers for virgin plastics, the stabilizers for recycling should, according to the manufacturers, be optimized for the requirements of recycling (first loop). Due to the confidentiality of the formulations, it is not possible to trace how this has been achieved.

Recyclers are in a proverbial quandary: post-stabilization is absolutely essential, especially for products with a longer service life. But since neither the composition and quantity of stabilizers still present in the recyclate nor the composition and quantity of recycling additives is known, it is not possible to assume "good practice". We were informed that there are empirical values out of experience here and that the additive manufacturers would also help to determine the concentrations for post-stabilization in individual cases. The situation is even less convincing if you consider the situation across several loops (second loop, third loop ...). In the worst case, we believe that risky peaks of additive concentrations in the recyclate or the product made from it can occur, especially for fast-moving products (packaging, for example).

4.2. Compatibility Mediators or Compatibilizers

Even high-quality sorted EoL-plastic fractions contain impurities in the range of 10% by weight and more. In today's practice, the impurities are regularly higher. It is therefore necessary to achieve good miscibility between the dominating polymer and the impurities. Even common polyolefins such as PP, PE or PS do not mix well with each other. Mixing is impossible if a non-polar sorting fraction like PP or PE contains impurities of polar polymers such as PET or PA. Non-miscibility regularly leads to workpieces with poor physical values. In order to improve miscibility, so-called compatibilizers are offered for recycling. These recycling additives are also added to the melt in the extruder. This is where the chemical reaction takes place that is intended to improve miscibility.

Chemically, compatibilizers consist of a polymer chain that mixes well with one of the polymers (e.g. the non-polar one) in the extruder and grafted reactive groups that form a covalent bond with

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the other, non-miscible polar polymer. The number and type of compatibilizers and their active ingredients is very diverse, also because there are many medium-sized "garage companies" on the market in addition to the large polymer manufacturers. The selection of products in Table 1 is therefore not representative. In most cases, epoxides and anhydrides are used as active ingredients.

The situation regarding compatibilizers is unclear. Without clear and comprehensible information on the active ingredients and frame formulation, their use cannot be recommended. This lack of clarity in the market also poses a further risk to consumer protection.

4.3. Repair-Systems

Similar to compatibilizers, repair systems also use reactive substances that react chemically with the polymers in the extruder. For repair systems, literature mentions active substances based on epoxides, oxazolines, oxazolones, oxazines, isocyanates, anhydrides, acrylic lactams, maleimides, phosphonites, cyanates, alcohol carbodiimides and esters [11].

Repair systems function chemically in such a way that the damage caused by e.g. ageing in the polymer is chemically "repaired" by chain lengthening, chain shortening or cross-linking the polymer chains. This requires reactive additives that carry out chemical changes directly on the polymer molecule in various forms.

4.4. Odor Reduction

Recyclates often have unpleasant odors that rule out their use in the production of higher-quality products. Here, specially developed recycling additives can reduce unpleasant or intolerable odors. These additives work according to two different principles: Absorbers or reactive substances [11]. While absorbers (e.g. zeolites) are largely unproblematic, reactive substances must be viewed critically. The reasons are similar to those already explained for compatibilizers and repair systems. The reactive substances used include the epoxides and anhydrides already mentioned.

4.5. Toxicological Concerns

For compatibilizers—similar to repair systems and reactive odor removers—the toxicology of the ingredients as well as their reactivity itself must be discussed [15]. It must be ensured that no reactive residues of these active ingredients, which are continuously added to the material in the extruder in the percentage range, are present in the end product. There is often a lack of suitable analytical methods to check this. If the active ingredients are unknown, monitoring is impossible.

When using reactive additives, it must also be taken into account that—in contrast to the use of such additives in virgin plastics—the chemical environment (polymers, additives) of EoL-plastics is less well known. Any "side reactions" that lead to the formation of undesirable compounds can be predicted (with restrictions) for virgin plastics. This is not possible for a largely unknown plastic matrix from the waste sector. Even high-quality processing cannot clearly define which side reactions will occur, neither for the polymer area nor for the additives contained, if the active ingredients are unknown (confidential). These additives therefore pose a residual risk that cannot be excluded with the desired degree of certainty.

What are the consequences of this residual risk? After all, the manufacture of virgin plastics also produces products using reactive substances via similar reactions. And other forms of recycling (chemical recycling) will also produce hazardous substances. In the case of virgin plastics production, the potential reactants are known and the reaction paths are therefore better defined. There are detailed product controls and emission limits for pollutant are adhered to. Chemical recycling provides a raw material for the production of plastics, but not an end product. Solely material or mechanical recycling provides a product that, depending on the type, can have very intensive consumer contact.

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In summary, we assume that only the disclosure of the composition (frame formulation) of recycling additives will allow to control recyclates and recycled products and thus eliminate the toxicological concerns outlined here.

4.6. Legal Aspects

Chemically, recyclates are to be regarded as mixtures (for definitions, see Section 2). Whether they are also legally regarded as "mixtures" depends on whether the recyclates are still waste or already a product. The EU Commission has therefore commissioned the Joint Research Center (JRC) to develop technical proposals for EU-wide criteria for the end-of-waste (EoW) status of plastic waste. Such studies and recommendations generally serve the EU Commission as a basis for establishing legal regulations. The JRC proposes here: "End-of-waste status is granted at the moment at which the output material of the recycling operation is a polymer or plastic that is ready for use in the production of new plastic products or articles containing plastic parts and complies with the full set of EoW criteria" [16], here Section 6.1.3.3].

Accordingly, if a recyclate no longer needs to be further processed for subsequent material use, it is no longer considered waste, but a product. From this point onwards, substance legislation (REACH, CLP) would then apply. The processor or the processing third party would be legally treated as the manufacturer of a mixture (registration obligation, authorization, notifications in the supply chain, etc.).

Due to the special status of polymers, which do not have to be registered in accordance with REACH Article 2 para 9, the need for mandatory registration of recycled plastics could become obsolete. However, this does not apply to monomers, additives and reaction products. At this point, recyclers (producers of regenerates or processors) would be obliged to register the recycling additives they use. This would be a high legal hurdle for recyclers.

On closer inspection, however, this obligation may not apply because the recycler can fall back on the so-called "recycling privilege" (Article 2(7)(d) REACH). However, in order for the recycling privilege to apply, all substances contained in the recyclate must be identical to an already registered substance, and the information on hazard characteristics, e.g. from the safety data sheet, must be available. For recyclates obtained from virgin plastics or the compounds (polymers + additives) produced from them (production scrap), it can therefore be assumed that the recycled material is identical to the source material. Furthermore, it can be assumed that by 2024 all common additives will have been registered with the ECHA by at least one of the commercial suppliers of additives.

We assume that most of the recycling additives are also registered, as very many of the principal stabilizer classes were not different from those used with virgin material [7, p. 999]. But as a rule, they have not been contained in the respective source material. Rather, they are added to the material directly after the recycling process (at the recyclate processor) or, in the case of regenerate, shortly before. In our opinion, they can therefore no longer be classified under the facilitations of the recycling privilege.

If the active substance of the recycling additive is an important ingredient of the future product (otherwise it would be dispensable), it can no longer be assumed that the recycled material is identical to the starting material. This applies even more to additives that make reactive changes to the polymer molecule and are used in the percentage range (<5 to >10% by weight). Without knowledge of the chemical identity of these substances, the applicability of the recycling privilege is questionable.

And it would be even more difficult if a mixture could not be described chemically. There is then the possibility that it would be classified as UVCB substance (substances of unknown or **v**ariable composition, **c**omplex reaction products or **b**iological materials). This would have serious legal and factual disadvantages for recyclers and their products.

In summary, we assume that it will be legally difficult or even impossible for recyclers to claim the recycling privilege when using an additive fully or partly unknown to them.

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4.7. Outlook

Ecodesign aims to integrate environmental aspects into product development at an early stage in order to reduce negative environmental impacts throughout the entire life cycle of a product. With the new Ecodesign Regulation (ESPR [17]) adopted in 2024, the EU intends to broaden the scope of ecodesign. It also provides for the minimization of Substances of Concern (SoC) in products. Following ESPR, a Substance of Concern is one that meets any of the following four criteria:

- It has already been identified as a substance of very high concern (SVHC) under the REACH regulation (Article 57 and 59(1)).
- It exhibits any of the hazardous properties listed in Part 3 of Annex VI to the CLP Regulation (Regulation (EC) No 1272/2008).
- It is covered by the Regulation on Persistent Organic Pollutants (POP Regulation) (Regulation (EU) 2019/1021).
- It "negatively affects the reuse and recycling of materials in the products in which it is present".

The announcement of the digital product passport (DPP) is particularly relevant here. In the future, information on the chemical composition of a product is to be passed on in the EU via a DPP in the supply chain to the consumer and the post-consumer sector. With the product passport, ecodesign thus supports the Chemicals Strategy for Sustainability (CSS), which calls for the minimization of substances of concern and the provision of information on their chemical composition and safe use. In future, the question will arise as to whether recycling additives contain or build substances of concern and how the use of recycling additives should be included in the preparation of the DPP. A concrete starting point for recycling additives is Article 7(2) of the Ecodesign Directive [17].

Circular economy also benefits from the DPP. If it is known what the chemical composition of products is at the end of their service life, they can be recycled more easily. This also applies if products are proven not to contain any substances of concern.

In view of the sensitivity of the topic of recycling additives described above, whether the industry should wait until the legislator provides final clarity is a question that market participants should ask themselves.

5. Conclusions

The example of lead shows how important it is to be careful when selecting additives and also to think about future recycling. Since November 29, 2024, lead may no longer be used in PVC products and PVC products containing lead (> 0.1 % by weight) may no longer be placed on the market in the EU [18]. For certain applications, such as products containing recycled PVC, longer transitional periods apply. However, the ban on lead in PVC products, especially imports, must be enforced and monitored, as lead stabilizers for PVC are still freely available on the global market (e.g. in Asia [19]).

In order to be able to practice high-quality mechanical or material recycling, it will be necessary to use chemical additives (recycling additives). In order to avoid falling into the proverbial recycling trap a second time after the risk recycling of currently banned additives, it is necessary that the composition of these products, which are important for the circular economy, has to be transparent (disclosure of the frame formulation).

The recycling additives commonly used today are very diverse and can, for example, perform post-stabilization for recyclates or reduce unpleasant odors. There are also products on the market that can repair damaged polymers. Additives are also available that improve the miscibility of inhomogeneous sorting fractions.

The authors have attempted to find out the chemical identity and frame formulation of these plastic recycling additives. This information is not available. Even in the safety data sheets there is no transparency. However, it is known from discussions and the literature that highly reactive substances are sometimes used for these products.

The current situation is unacceptable [15], especially for medium-sized companies in the recycling industry. If recyclers use an unknown substance or an unknown mixture, they cannot "hide" behind the confidentiality interests of the additive manufacturers; they are and remain responsible for the recyclate/product produced. In regulatory terms, the necessary transparency of recycling additives can be established via the future digital product passport.

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