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PVC recycling management*

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Abstract: PVC is the second most important polymer worldwide and a large-scale chemical product. Thanks to its excellent cost/performance ratio and outstanding chemical and environmental resistance, it is today mainly used for long-life applications. In some countries like France, PVC is used too in large volume for bottles. Pure PVC scrap can be recycled without any problems. Although many applications for such products of recycled PVC have been developed and pilot plants for recycling exist, only small volumes have been recycled up to now. Only bottles made from PVC for drinking water in France, which is a large market, are already separately collected, recycled in large quantities, and transformed into such articles as water pipes. Specialist organisations deal with this business. In such cases like kitchen waste, where PVC is part of mixed plastics waste for example, sorting and separation of the PVC is necessary.

1. INTRODUCTION

1.1 The significance of PVC

PVC is a chemical product produced on an industrial scale and represents the second most important polymer worldwide. This is illustrated in Fig. 1, showing the course of development for this large-scale product over the past two decades. PVC is supplied in powdered form by the raw material producers (generally big chemical companies) and comes in a wide range of different types. Compounders or converters then mix processing aids, stabilisers and other additives into the powder. The PVC is processed into semi-finished and finished products using either the processing units employed for other thermoplastics or, in most cases, specially-modified plant. The reasons why PVC enjoys such widespread use are the following:

- it is the thermoplastic offering the best price-to-performance ratio.
- it has a particularly broad property range and can be modified within extensive limits (from hard and rigid through to soft and rubber-elastic); one of its attributes is a particularly pronounced resistance to chemicals.
- it can be processed easily and in a highly versatile manner, and single-sort PVC offers excellent recyclability.

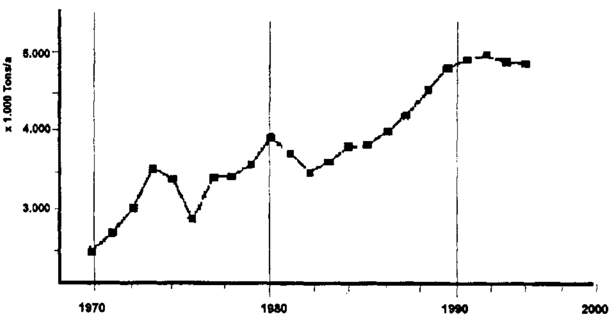


Fig. 1 Annual PVC consumption in Western Europe since 1970 (from Bühl, EVC).

The excellent cost/performance ratio of PVC and the fact that it can be used to achieve a wide variety of tailor-made formulations explain its success in markets as different as building and construction (more than 50% of all PVC sold), cables, the automotive industry, electrical appliances, medical devices, packaging (about 15% of the total) and many other sectors (Fig. 2)

Its outstanding resistance to degradation often makes PVC the ideal choice for long-life applications (30 years and more without any paint or corrosion protection) such as pipes, window profiles, floor covering, liners for the

*See Refs [23–25].

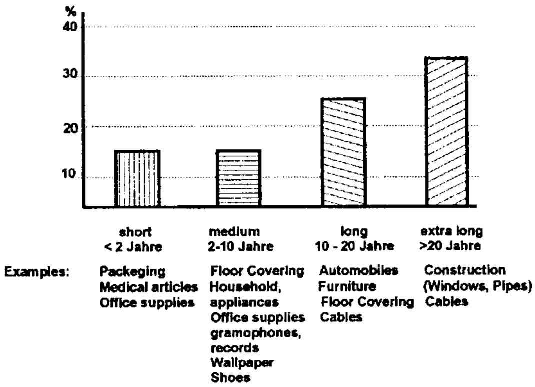


Fig. 2 The average use of PVC products in Western Europe (from Bühl, EVC).

protection of ground water etc. In the field of human health, PVC has certainly been the most-used and best-researched plastic for many years. Hospitals throughout the world use PVC blood pouches, transfusion and stomach piping, surgical gloves, oxygen tents and many other vital devices.

1.2 A brief introduction to the material for an easier understanding of its recycling

PVC is produced from vinyl chloride by radical polymerisation. Its structural formula is as follows:

$$x\mathrm{CH_2{=}\underset{\displaystyle Cl}{\underset{|}{C}H}} \rightarrow [\mathrm{CH_2{-}\underset{\displaystyle Cl}{\underset{|}{C}H}}]_x$$

vinyl chloride → polyvinyl chloride [PVC]

The position of the chlorine atom on the hydrocarbon chain leads to high polar secondary valence forces, which are responsible for the relatively high freezing temperature of 80 to 90 °C. These forces, however, also make it possible for a high percentage of low-molecular (or polymeric) liquids containing similar polar groups (so-called plasticisers) to be bonded into the polymer. This is due to the secondary valence gels that these liquids form with the polymer. The freezing temperature is then lowered—something which is generally exploited to the extent where PVC made up in this way still retains its elastomeric character at room temperature. The polar nature of PVC is also responsible for the fact that only polar liquids can penetrate the PVC and dissolve it. PVC possesses a very high resistance to apolar substances; in other words, it has excellent chemical resistance. It is also the polar structure of the polymer that permits PVC to take relatively high filler contents—a capability that is even more pronounced in plasticised PVC. This is the reason for the prolonged service life of articles such as floor coverings, since these can contain up to 50% by volume of filler.

The drawback to the relatively loose molecular bond between the chlorine atom and the polymer chain is that chlorine atoms can split off during processing already, at temperatures of above 140 °C or so. This is a problem that was satisfactorily solved many decades ago through the development of additives—so-called stabilisers. These substances, which are mostly metal-based compounds, are mixed in with the polymer during compounding in quantities of some 2%, in conjunction with other aids. They give the products sufficient processing stability and a very long service life, including a sufficient level of light stability.

The loose bond of the chlorine atom and the fact that chlorine accounts for 56% by volume of the polymer give rise to a further, generally much-valued property: the inherent flame retardancy of PVC.

PVC without plasticiser, so-called rigid PVC, solidifies amorphously (with the exception of a small crystalline component). This means that, once the freezing temperature has been exceeded, rigid PVC only converts slowly from the elastomeric state, which persists to approximately 170 °C, to the state where it has a sufficiently low viscosity for processing on an extruder, at approximately 200 °C. This gradual transition constitutes a particular advantage for a large number of forming and joining techniques, such as thermoforming, bending and welding, etc. This, in turn, is the reason why PVC is in such widespread use as a construction material.

2. PVC AND SUSTAINABLE DEVELOPMENT

Crude oil is the most common raw material used in the production of plastics. In Western Europe, only 4% of the crude oil used is necessary to provide feedstock for all the plastics produced (only 0.25% for PVC) whilst 86% is used as fuel for heating, transportation and the generation of electrical energy. Thanks to the light weight of plastics parts, the energy saved through the use of these parts is often many times greater than the energy value of the crude oil 'invested' in the plastic raw material. Using the relatively limited hydrocarbon resources of our Earth for plastics thus frequently constitutes one of the best environmental choices.

PVC has an outstanding performance in this respect, since 56% of PVC is made up of salt (NaCl), which is in virtually unlimited supply.

Comparative life cycle analyses often show the excellent environmental performance of PVC solutions, as does the one carried out by Richter, Switzerland, on window frames. PVC is preferable to wood and aluminium even without recycling. Increasing recycling rates will give PVC an even greater environmental advantage.

The SEM study coordinated by the Norwegian government came to a similar conclusion for packaging: 'SEM's analysis does not therefore provide any grounds for imposing the phasing-out of PVC in disposable packaging. Parts of the analysis clearly indicate that PVC, on the whole, is a better alternative in environmental terms than its potential replacements' [1].

A recent Dutch study (TNO-1994) confirmed earlier results that had been found in several countries for clean waste incineration with heat recovery: PVC has no negative effect on emissions to the air.

In incinerators, the addition of plastic waste, including PVC, leads to better, more stable incineration conditions with improved burnout and a general tendency towards reduced emissions, as is shown by German [2] and French [3] results.

The 'Enquête-Kommission' of the German Bundestag recently concluded that the substitution of PVC by other materials can have negative effects on human health and that PVC should not therefore be substituted by other products without a thorough investigation of the environmental and economic effects of the substitutes. It called for the further development of existing ecologically sound methods of PVC recycling [4].

3. THE MECHANICAL RECYCLING OF PVC

3.1 General

The return rates for post-consumer PVC are still very low, at < 5%, this being due primarily to the long-life applications in which PVC is employed, most of which date back no more than 20 years.

When it comes to in-house production waste and also trim from building sites, by contrast, almost all of this is now returned to the semi-finished product manufacturers, on account of the extreme rise in the cost of disposal. Since this is single-sort and generally clean waste, it is fed back into the production cycle for new semi-finished products. By far the majority of in-house PVC waste is now reprocessed. Only small residual amounts remain to be disposed of by public disposal systems (landfills, incinerators). This form of reprocessing is seen to operate on a break-even basis, particularly when the savings on disposal costs are taken into account.

Thanks to the comprehensive studies that have been conducted by a large number of research institutes and industry and also thanks to the experience gained through regular operation, we now have a very clear picture of

1. the stability of single sort and clean PVC over many recycling runs (Fig. 3)
2. which methods make sense in economic and ecological terms.

From all the experience that has been gained throughout Europe it has been seen that lightly and

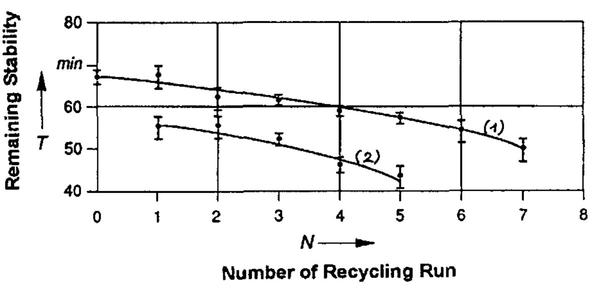


Fig. 3 Stability dependence of recycling runs for PVC-film (1) PVC-S, extrusion; (2) PVC-E, mill.

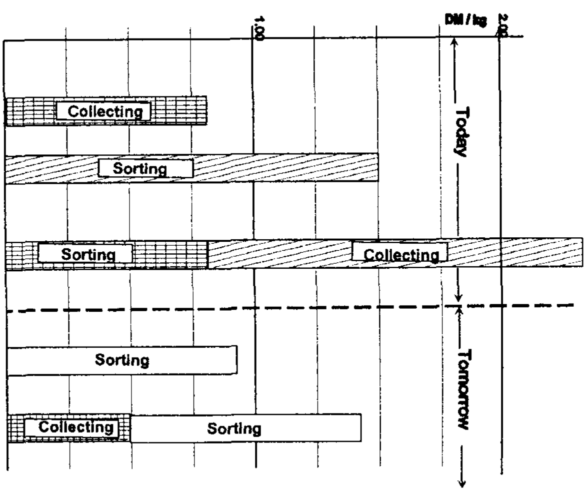


Fig. 4 Cost of collecting and sorting of household packaging waste (DSD).

heavily soiled mixed plastic waste containing PVC can only be separated at a high cost into a more or less clean PVC fraction on the one hand and a recyclable fraction of other thermoplastics on the other hand (Fig. 4). The experience gained with packaging waste in Germany has shown that a gate fee of about DM 800/t for recycling is necessary (without the logistical costs). Open-minded governments have already drawn their consequences from this and, like France, now only require the virtually single-sort PVC bottle fraction within this waste to be channelled back for recycling.

3.2 General quality requirements on PVC recyclate

Whether a recyclate can be successfully marketed or not will depend on its price, its quality and its availability and also on the demand for it. These factors, in turn, are interlinked. The aim must therefore be to achieve a recyclate with precisely defined properties that can be fed into an existing processing cycle again with the fewest possible problems, since existing production capacity is essentially tailored to the characteristic properties of virgin PVC [5,6]:

- K-value or viscosity number: measure of the flowability of the melt and the possibility of remelting;
- Particle size: measure of conveyability and suitability for transfer to silos and mixing;
- Grain morphology: measure of filler absorption capacity and gelation performance;
- Bulk density: measure of free flowability and remelting output;
- Thermostability: measure of residual stability and post-stabilisation;
- Volatile components: measure of moisture content, inter alia;
- Cleanliness, fish-eye formation: measure of soiling.

Tight tolerances are characteristic of high-grade PVC and are crucial for trouble-free production. Any converter wishing to employ recycled PVC will thus inevitably require a quality profile that comes as close as possible to that of virgin material. Since this can scarcely be achieved in practice, two options remain open, depending on the quality of the recycled product:

- direct remelting in the form of 100% PVC recyclate,
- mixing with virgin PVC employing compounding techniques.

It should, however, be added that the second option is frequently not feasible, or would only be possible after highly elaborate tests. If the applications involved are long-term ones, as is frequently the case with PVC, then this calls for the appropriate long-term durability, which cannot be recorded in simple short-time tests. Other examples include medical applications where the necessary product reliability and cleanliness would not permit the use of recyclate as a matter of principle.

A further problem, and one which is generally overlooked, is that it is always necessary to have certain minimum quantities of uniform, recyclable preliminary product in order to be able to produce a sufficiently large, uniform quantity of new raw material. This also applies if the recyclate is to be mixed with virgin raw material. In many cases, however, these minimum quantities are not available. This then excludes mechanical recycling, unless there is a readiness to launch major information campaigns and accept lengthy storage times and long transport routes. It has been seen that this constitutes one of the chief obstacles to the recycling of mixed plastics waste of any type.

3.3 The mechanical recycling of mixed waste in or containing PVC

A number of PVC post-user waste recycling schemes are running at an industrial or pilot level in several countries, including:

- bottle recycling in France (see following chapters) and in many other countries
- tube, pipe and cable ducts in the Netherlands and Switzerland—back to same or similar applications [13–15]
- cable insulation, in France and Italy, for coextruded garden hoses
- floor covering in Germany back to floor covering (often in a layer covered by virgin material [7])
- computer housings in the UK back to the same application
- window profiles in Germany into the interior layer of coextruded window profiles [9–11]
- and others.

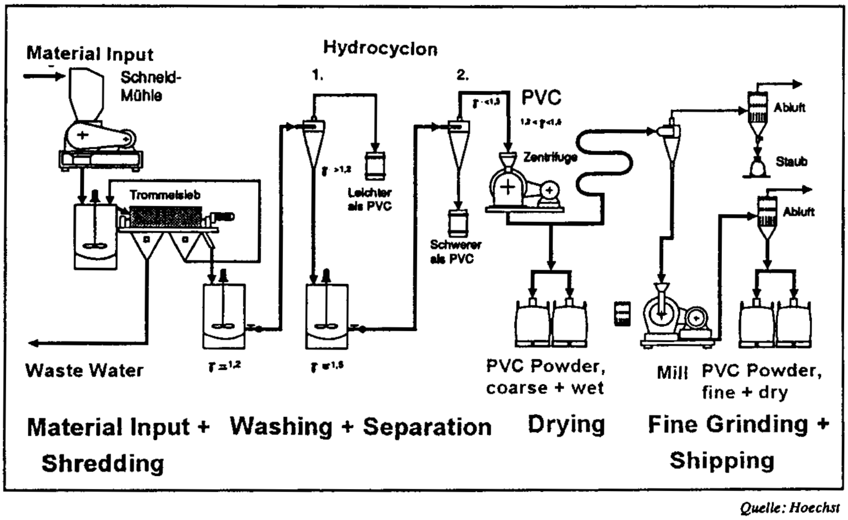


Fig. 5 Recycling plant for PVC film.

Development work on 'leather-like' PVC/PUR foam/PC-ABS for three-layer dashboards and calendered PVC sheets from seat covers in scrap cars is under way in France.

Figure 5 shows a plant in Germany which has been constructed for the cleaning of soiled film and sheet post consumer household waste.

3.4 A successful example of mechanical recycling for post-consumer plastics packaging waste

The recycling of PVC bottles in France is one example that shows in a particularly clear fashion that even waste which previously found its way on to landfills along with domestic waste can be economically profitable.

PVC bottles are in widespread use in France—particularly for non-carbonated drinking water. GECOM, an association set up jointly by the PVC and mineral water industry long before the first packaging decrees appeared in Germany and France, launched its first collection and recycling programmes in the Eighties. These became widely known by the name of one of the association's major schemes: 'Operation PELICAN'.

In 1993/1994, the creation of Eco-Emballages, the French green dot system and its plastics partner Valorplast, led to the setting up of three companies linked to Valorplast. These give a take-back guarantee for collected PVC bottles ('RECY PVC'), PET bottles ('RECY PET') and HDPE bottles ('RECY PEHD'). The collection is managed by local authorities (or their subcontractors), with technical advice from Valorplast's regional delegates and a subsidy from Eco-Emballages (FF 1,500/t; a higher amount is currently under discussion), financed through the 'green dot' contribution of packers/fillers.*

The French Eco-Emballages system differs from the German DSD system in three major respects:

- it will only be operating on a full scale in about ten years (2002) in order to leave enough time for the optimum economic and environmental conditions to be established on a local basis
- it includes full recognition of energy recovery for small packaging*
- consumers save a great deal of money thanks to the two points above

By the end of 1995, about 15% of the French population was linked to a plastic bottle collection system already. In most cases, this is by means of 'bring systems' that are still installed under the GECOM voluntary scheme, but there are an increasing number of multi-material kerbside collection programmes as part of Eco-Emballages pilot schemes.

* It should be noted that in the French system, the separate collection of plastics consumer packaging is limited to bottles. Small packaging (typically PE and PP films and pouches, PS cups, etc., with an average weight of 5g) ought to remain in the normal waste stream and be increasingly fed to clean and efficient "waste to energy" incinerators (with a financial contribution from Eco-Emballages of FF 100 to 350/t for small packaging, providing sufficient amounts of 'large' packaging are collected).

Today, the vast majority of bottles collected in France are PVC: about 200 million bottles (8000 t of PVC) were reprocessed in 1995, corresponding to approximately 5% of the French PVC bottles ultimately targeted for collection and recycling.

This illustrates the relatively high participation of the population in those areas where a collection scheme is already established: more than 50% in many areas—a good score when it is considered that this is something relatively new for the French.

A recent survey conducted by the CSCV consumer organisation shows clearly that the majority of the French would like to participate in plastic bottle collection schemes (as they are increasingly doing for glass bottles). At the same time, the vast majority of French consumers reject the idea of washing and collecting 5 g yoghurt pots at home (it takes 200 000 pots to obtain 1 ton of plastic).

3.4.1 RECY PVC—'The fifth French producer'

RECY PVC's shareholders are:

30% Elf Atochem
30% Solvay
25% Shell
10% Société Artésienne de Vinyle
5% Association of Mineral Water Producers

RECY PVC gives a take-back guarantee (currently at no cost) for collected bottles which are pre-sorted (to agreed specifications) and baled. Automatic fine sorting (99.98% PVC) and recycling is performed by companies under contract from RECY PVC (e.g. Micronyl-Wedco, SOREPLA, representing a workforce of approximately 50 for PVC alone).

The end product (flakes, but for the most part powder, in a particle size of between 500 and 1200 μ) is sold to PVC converters by the RECY PVC sales force, a team of seven people (see Table 1).

Full technical support for fine sorting, recycling process enhancement and application development, and also customer and laboratory service, is provided by RECY PVC's major shareholders and their laboratories. Table 1 forms part of the RECY PCV business schedule

RECY PVC is already a technical and commercial success today. The major technical problems involved in PVC bottle recycling have been solved.

Businesswise, RECY PVC is moving quickly towards the break-even point; under present conditions, this should be reached with an annual collection of close on 15 000 t of bottles.

The shareholders will then invest the cash that has been generated in increasing PVC bottle recycling capacity.

Existing capacity is to be extended by a modern, fully integrated PVC sorting and recycling unit in mid-1997.

All the French PVC bottles collected are already recycled today. The table above shows clearly that today more than half of all recycled bottles go to pipe. The high quality of collection, sorting and recycling

Table 1 Volume of PVC recycled from bottles by RECY PVC France

Application	1995	Estimate for 1997 as a function of collection* low	high
Pipes	4900 t	13 000 t	20 000 t
Fittings	700 t	1000 t	1500 t
Profiles	300 t	2800 t	4000 t
Floor covering	200 t	200t	500 t
Reinforcement sheet (for shoes)	1200 t	1500t	2000 t
Others (fibres, corrugated sheet, export, etc,)	1300 t	1500t	2000 t
Total	8600 t†	20 000t	30 000 t

*As a function of new contracts between Eco-Emballages and local communities and consumer participation
†Collection in 1995: 11 000 t

systems guaranties high purity, the key for this success. Only trace amounts of paper, hot melt (from labels) brocken glas, other polymers etc. can be tolerated.

ALPHACAN, together with ist mother company ELF ATOCHEM carried out pioneering work, but today all large tube and pipe producers of France (WAVIN, FRANCE TUBE, SOTRA etc.) use recycled PVC from bottles as does NICOLL (ETEX Group) for fittings. For 1997 the figures are expected to increase to 450 million of bottles for 20.000 kms of pipe.

By the year 2000 when ECO.EMBALLAGES is expected to be fully developed all PVC bottles could be recycled in the huge PVC building and construction market alone. But many more applications are under commercial development, as will be shown later.

3.5 Examples of the successful recycling of single-sort PVC displaying ageing and soiling after prolonged service for the same or similar application

In view of the strict standardisation that has been applied to the roofing sheet, window frames and pipes that have been in use for many years, the materials employed in these applications from different suppliers are highly similar or even identical. This means that waste from these applications has to be regarded as single-sort waste. It will be soiled and have degraded surface layers which have suffered a certain amount of damage through the influence of light. Examples of this type are described below.

3.5.1 PVC floor coverings and roofing sheet [7,8]

A prime example of how a whole sector can join ranks to tackle recycling is furnished by the *Arbeitsgemeinschaft PVC Bodenbelag Recycling e. V. (AgPR)* (Association for the Recycling of PVC Floor Covering), which was founded in April 1990. The Association's membership takes in some 20 raw materials and floor covering producers from Germany and other European countries who are working together to introduce nationwide collection schemes for post-consumer PVC floor covering and to channel this into recycling. The Association's members are contributing equal shares of the funding required.

The used flooring (which accounts for some 70% of the goods collected) is pre-sorted by hand and then coarsely shredded and finely ground to 0.2 mm in a central recycling plant. Screed, glass fabric, adhesive residues and any other contamination stuck to the flooring is retained by screens and pneumatic separators and hence, at the end of this preparation process, the PVC recyclate achieved has a degree of purity in excess of 99%, inclusive of fillers. Depending on whether the regrind is to be used for the backing layer or the intermediate layer, it is reformulated through the addition of plasticisers, fillers and other additives and fed back to the manufacturing cycle to make new calendered PVC floor covering. This type of multilayer PVC floor covering can accommodate a recyclate content of up to 70%.

Following the example set by the *AgPR* for floor covering, the *Arbeitsgemeinschaft für das Dachbahnen Recycling e. V. (AfDR)* (Association for the Recycling of Roofing Sheet) was set up in April 1993 with the aim of collecting and recycling used roofing sheet [8]. This used roofing sheet, plus the trim from newly-laid sheeting, is ground into a defined-quality powder in a central preparation plant which was brought into operation at the end of 1993. The Association's members then take this powder and use it for products in their respective ranges, such as for the sealing sheets required in tunnel construction. The experience gained in the course of the next few years will show whether new sheet can be produced with the recyclate obtained from used sheet, since this is an application where stringent guarantees are required.

3.5.2 PVC windows

Tests have been carried out to dismantle and grind 22-year-old PVC windows and then employ this 100% recyclate for the core layer of new, coextruded window profiles [9]. The core welds to the outer layer in virgin material, forming an indissoluble bond. Despite the high recyclate content of 66% of the overall profile, these windows complied with all the RAL quality specifications. They are currently undergoing in-service testing and will doubtless survive another 40 years or more before they need recycling again (Fig. 6).

Dismantling old PVC windows into their individual components is a time-consuming and hence costly process which can still be justified in the case of a low collection rate; this was the basis taken for a nationwide collection scheme in Austria [10]. When a similar take-back system was introduced for used PVC windows in Germany, a great deal of manual work was also involved in achieving re-usable profile material to begin with. At the end of 1993, the first two automatic recycling plants for old PVC windows

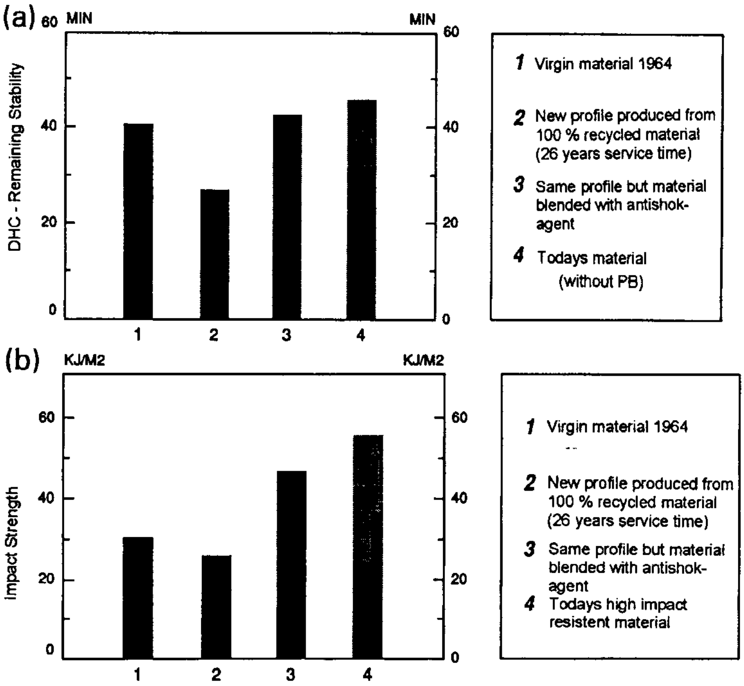


Fig. 6 (a) Thermostability of recycled material from old window frames. (b) Impact strength of PVC recylced from old window frames.

came on stream [11,12].

Taking the example of the plant in Behringen, the disassembly of the intact PVC windows and their segregation into individual materials involves the following stages:

Stage 1: The old windows, door units, roller blinds and profile sections in PVC are pressed together with the glass, reinforcements, seals and fittings and then coarsely shredded.

Stage 2: Following this initial shredding stage comes the first material segregation step: into glass, non-ferrous metals, ferrous metals, rubber and PVC.

Stage 3: The PVC segregated in this way is checked once again to ensure that it has been correctly sorted, has the dust removed from it and is then further shredded.

Stage 4: The PVC is cleaned and finely ground once again, and this is followed by the final cleaning stage. Other materials, separated into different sorts, are conveyed fully automatically to containers.

Stage 5: The PVC recyclate is stored in silos and processed into new profiles and sheet by coextrusion.

Stage 6: The other materials such as glass and metal, etc. are similarly sent for recycling.

In this way, it would seem possible to attain a recycling rate of 97.5% for the materials collected; only 2.5% of the material is not recyclable and has to be disposed of. As far as the PVC recyclate is concerned, colour alignment and a residual impurity component constitute a problem. This is why, in future, coextrusion with a core layer in recyclate and an outer layer in virgin material will be the type of production that comes to supplement existing production capacity.

3.5.3 PVC pipes

Manufacturers of PVC have been taking back left-overs from building sites and also used material from conversion and renovation work for many years [13,14]. The term 'used material' designates piping that has been in use for 10, 20 or 40 years but which is far from having reached the end of its expected life, which can extend to 100 years or more. Large-scale quantities of used PVC are not expected to become available until the year 2010 at the earliest. The amounts available today are thus exceedingly small, making it impossible for individual pipe manufacturers to set up an economic collection system.

The *Vereniging van Fabrikanten van Kunststoffleidingssystemen (FKS)*—Association of Plastics Pipe System Manufacturers—in the Netherlands has already been tackling this problem on a nationwide basis since 1991 [15]. All the big Dutch PVC, PE and PP pipe manufacturers are represented in the *FKS*. The material is collected from building sites by a jointly-organised container collection system and sent to a compounding plant. The first stage involves manual sorting of the PVC, PE and PP piping (NB: standardised pipes have identification markings on them), coarse grinding and the elimination of coarse impurities such as sand, seals and metals. In the second stage, the used material is finely ground to approximately 0.5 mm. With added blowing agent, this recyclate is then used for the foamed inner layer of a three-layer sewer pipe. The regrind component can be as high as 60% by weight here. A similar nationwide take-back scheme was introduced at the end of 1993 for Germany by the *Kunststoffrohrverband (KRV)*—Plastics Pipe Association—and the pipe manufacturers who belong to it. ISO and CEN view this development favourably and are preparing the necessary changes to the Standards.

3.6 Estimating market absorption capacity

While the mechanical recycling of single-sort residual materials from industry and trade is already running at a high level, the recycling of used PVC products has only been under development for a relatively short time. This is made clear by the case studies presented here which are aimed at single-sort or virtually single-sort recycling—and there are more such examples that could be given. All these recycling activities, however, not only offer opportunities but also come up against their limits. It rapidly becomes necessary to ask 'How much recyclate can the PVC market absorb?' or, put in different terms, 'How much virgin material can be substituted by recyclate?'

Infrastructure, competition, cost effectiveness, existing machine fleet, quality, standards and, not least, consumer acceptance are factors that influence any form of recycling, and solutions must be found for these.

As with all other plastics, determining the market absorption capacity for PVC recyclate is a highly complex process, since market absorption is affected by a large number of the factors mentioned above at one and the same time. If the focus is placed solely on technical aspects by way of a simplification, then it becomes possible to work out an initial estimate. The technical aspects take in the degree of segregation, the maintenance of functions, suitably adapted Standards and the availability of the right type of production capacity, such as multi-layer and coextrusion plants.

The amount of recycled PVC that will be available over the next ten years, however, will be limited to about 10% (estimate) of the production figure for virgin PVC. The main reason for this is the long lifetime of most PVC applications and hence the low level of PVC waste that will be available in the years 2000 to 2005.

As the example of pressurised pipes for drinking water shows, there are also limitations that cannot be overcome which make it impossible for recyclate to be fed back into the same application. These include food contact and medical applications where recyclates are unsuitable on hygienic grounds alone.

In addition to the other methods that can be employed for recycling PVC (i.e. feedstock recycling and incineration with energy recovery), it is also important for new markets to be located. A number of highly promising examples of such markets are presented below.

3.7 New applications [24]

3.7.1 Greater security and less noise in car parks through paints containing recycled PVC particles
High noise levels and low coefficients of friction in car tyres are the main problems encountered in car parks. Paint producer Monaco Sol, Monaco, working in cooperation with RECY PVC and Elf Atochem, has developed the PU and epoxy-based 'Mona Bleu' paints, which provide rough surfaces with improved properties thanks to the addition of up to 10% recycled PVC.

The particle size and morphology of the PVC have been optimised together with the basic composition of the paint and the viscosity and stability of the suspension. The most significant results are summarised in Table 2.

The addition of recycled PVC doubles the coefficient of friction. This dramatically improves safety on wet surfaces. The noise level decreases by the considerable margin of approximately 20 decibels.

The surface of the PVC particles is slightly altered by the paint components, ensuring a perfect bond between paint and PVC. This explains the excellent abrasion resistance revealed by the TABER abrasion tests performed.

Table 2 Coefficient of friction and noise level in car parks with PVC-modified paint

Name of car park	Château de Plaisance		Les Jardins d'Azur	
Paint contains recycled PVC	no	yes	no	yes
Coefficient of friction*				
dry surface	0.36	0.82	0.27	0.86
wet surface	0.17	0.33	0.17	0.32
Noise level†				
max. (in first bend*)	92 dB (A)	72 dB (A)		
integrated total	80 dB (A)	62.4 dB (A)		

*Measured with pendulum S.R.T

†Measured with an integrating sonometer with a memory, 125 msec intervals , Renault 19 equipped with Michelin X M+S 100 tyres, same distance covered including 3 bends, same speed (engine stopped).

Source: Centre d'Etudes Techniques de l'Equipement, Nice.

Ministère de l'Equipement, des Transports et du Tourisme, 20.7.1994.

The first car parks in Southern France are soon to be equipped with paint containing recycled PVC from bottles. This will lead to a higher level of safety and less noise.

3.7.2 A new high-performance sound protection wall in recycled PVC

The photo (Fig. 7) shows an element (70 cm wide) of the new patented sound protection wall that is based on recycled PVC and has been developed by Eco Recyclage, St. Eusebe, France.

Each element is made of recycled PVC sheet (between 50 and 80% from bottles, 20–50% from window profile and sheet) extruded by VEKA, France, with a PMMA anti-protection layer and an anti-graffiti coating. The inside, turned towards the source of the noise (motorway, railway, etc.), which is thermoformed and perforated by Saillard PLV and Cahors, guides the sound to two internal absorbing layers of glass wool in the centre. This system proved to be extremely efficient in tests performed by the Centre d'Etudes Techniques de l'Equipement Strasbourg (Ministère de l'Equipement, des Transports et du Tourisme):

- coefficient of absorption: more than 0.70 (road version)
- coefficient of transmission TLT: more than 30 dB (A)
- category: 'very high absorption'

The elements are delivered ready for assembly: two vertical metal bars and longitudinal concrete beams hold the elements in place.

This development is receiving support from the French Ministries of the Environment and Industry (drire and ademe), Eco-Emballages and Valorplast.

A first sound-protection wall of this type is currently being installed by AREA and the Rhone Alpes Département near Annemasse, France, to protect a residential area from motorway noise. A second test is under way alongside a TGV (high-speed train) line in Eastern France.

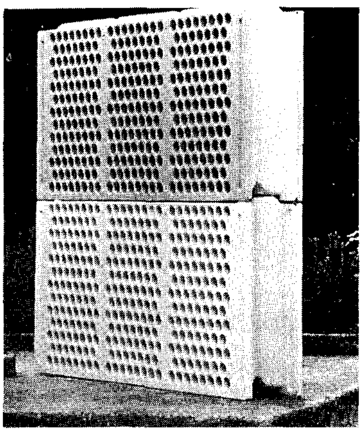


Fig. 7 New sound protection system based on recycled PVC.

3.7.3 Twenty to thirty PVC bottles keep you warm: recycled PVC in textiles

One of the most recent and most spectacular developments has been pullovers (see photo Fig. 8) made of PVC fibres that are based entirely on recycled post-consumer bottles.

RHOVYL of Tronville en Barrois, France, was founded in 1948 and is today number one in the world for chlorofibres (main applications: warm, comfortable underwear for extremely low temperatures

Fig. 8 Pullovers manufactured from recycled PVC.

and textiles with inherent flame retardant properties). Since mid-1994, the company has produced fibres from PVC bottles recycled by SOREPLA—Neufchateau/Vosges, France and sold by RECY PVC. The solution-spinning technique makes it possible for the pigments to be removed from the bottles.

As a result, the subsequent dying process is not restricted to dark colour shades—any colour from natural and very clear to dark is feasible.

In this initial development, carding, blending with 30% wool and dying are performed in the traditional way by PEIGNAGE DUMORTIER of Tourcoing, France, and the knitting is done by Filature de l'Avesnoise, France. The pullovers are sold by LA DUNOISE of Dun sur Auron, France, a company that has specialised in high-quality textiles for 50 years, marketing them under the trade name 'Charles Dubourg' in 19 countries.

The main difficulties encountered in spinning a solution of recycled PVC bottles came from impurities. These too frequently plugged the tiny openings of the spinning head. With the help of RECY PVC and ELF ATOCHEM's R&D laboratory at St. Fons, France, it proved possible to identify the nature of these impurities, enabling RHOVYL to modify its filtering equipment and adapt its manufacturing parameters.

The cooperation of all the partners involved in the supply and manufacturing chain has been the key to this success.

New textiles made of recycled PVC bottles are already under development. These include other types of pullovers, and also sweaters, caps, socks and gloves.

4. FEEDSTOCK RECYCLING

The large fraction of mixed plastics waste that is obtained when packaging is segregated from household waste contains a small percentage of PVC which would make feedstock recycling practicable here. All the methods that have been employed for feedstock recycling in pilot plants to date, however, involve restrictions on the permitted share of PVC or plastics containing halogen on plant engineering grounds [18]. The hydrogenation technique employed at the KAB plant in Bottrop, Germany, constitutes an exception here, since this coud cope with a PVC component of up to 10% [16].

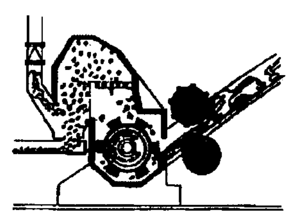
Blast furnaces also impose a limit of <2% Cl (= <4% PVC) on waste of this type treated in this way, which they use to inject in as a reducing agent for ferric oxides [17].

In addition, there is a further type of waste which is even more problematical in this respect and which will need to be recycled in future. This is the fluff fraction of shredder waste from scrap cars. More than 300 000 t/year of this waste is obtained in Germany alone. A PVC and halogen content of 10% or more has to be expected, depending on the age breakdown of the cars being shredded. This age breakdown is shown in Fig. 9. If waste of this type is to be channelled to the plants referred to above, including to blast furnaces, then either a cost-efficient means must be found of segregating materials that contain halogens and processing these separately or a low-cost dehalogenation method must be employed for the plastics concerned. LINDE-KCA-DRESDEN GmbH (a subsidiary of LINDE AG) already offers a plant of this type for throughputs of up to 8 t/h. A description of this plant will be included below, although the current subsidy arrangements whereby customers are allowed to take the agglomerated mixed plastics free of charge, means that it has not managed to become established in industry.

Situation

Cars per year	>2.000 000
Plastics content in old cars	>10 %
Weight of car body	1.000 kg
Weight of Plastics Waste	>200.000 t

Shredder Mill



Average Content of Plastics in the Shredder Waste

22 % PP + PE	44.000 t/a
30 % PUR	60.000 t/a
7 % PVC	14.000 t/a
7 % PC-Blends	14.000 t/a
7 % PA	14.000 t/a
5 % ABS	10.000 t/a
6 % Crosslinked fiber reinforced	12.000 t/a
16 % Other Thermoplastics	32.000 t/a

Fig. 9 Waste from car shredding.

4.1 Degradative extrusion for the simultaneous preparation, dehalogenation and liquefaction of mixtures of dissimilar thermoplastics waste [19]

Figure 10 shows a degradative extrusion plant in diagram form. This is made up of standard commercial plants centred around a counter-rotating twin-screw extruder as the key process component. The waste,

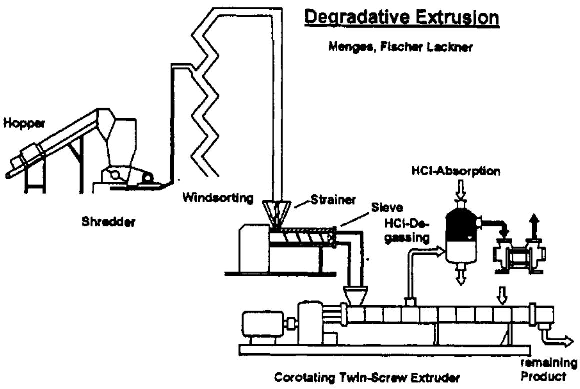


Fig. 10 Degradative extrusion.

shredded to approximately 8 cm in diameter, has the metal, glass and ceramics separated from it by a pneumatic separator and is then fed to a robust single or twin-screw extruder, fitted with a screen at one end. The melt extruder thus serves to melt the heterogeneous mixture of the different plastics at <250°C and to eliminate all the non-fusible components via the screen. The filtered melt is then transferred under pressure to the second screw unit—the co-rotating twin screw extruder. Here, the chlorine and other halogen atoms are removed from their bonds with the hydrocarbons in a matter of seconds through being exposed to shear and a melt temperature of 400 °C. In a downstream degassing zone, the halogens are then eliminated as hydrogen halides, together with other volatile substances. The halogen halides can be readily separated, such as by introduction into a water bath, and then recovered as Cl-source for the production of new vinyl chloride what is the monomer of new PVC. Where there are small quantities of halogenated plastics in the feedstock, the remainder of the melt is liquid and solidifies at approximately 100°C to form a wax-like product. If the feedstock mixture contains a very high halogen component, all that remains of the melt after degassing is a type of coke. This coke is immediately scraped off the walls of the screw unit by the tightly-intermeshing screws and discharged as a free-flowing, fine powder. This can then be recycled as a fuel in lignite gasification plants or refuse incineration plants.

Since degradative extrusion is not yet operating on an industrial scale, the costs of the process as a whole have to estimated on the basis of the extensive studies that have been carried out [20,21] and can be put at between DM 200 and less than DM 300/t. Since plants of this type simultaneously convert mixed and soiled plastics waste into a more readily manageable, sterile form (granules, powder, liquid) and reduce the halogen content to <0.2%, they hold very good prospects for the future, precisely for this type of plastics waste which contains a high level of chlorine. Only the inorganic, non-volatile chlorine compounds remain in the products.

These plants exploit the fact that the halogen atoms are only bonded very loosely to the main polymer chains and hence detach themselves spontaneously from the hydrocarbon chains of the polymer molecules in the form of hydrogen halide once a temperature of 270 °C has been attained. At a melt temperature of 350–400 °C and with the high shearing forces that prevail, the bonds are so loose that dehalogenation to a dechlorination level of <0.2% takes place within a matter of seconds once ambient pressure is attained.

If prices are calculated on a fair basis, then this method can readily compete with the visbreaking plants that are operated by companies such as KAB and BASF as the preliminary stage to the feedstock recycling of mixed plastics waste. This is because the same process, i.e. the elimination of halogens from the polymers, can take up to several hours in the visbreaking plant as a function of the method employed and the temperature, and handling a polymer melt at a temperature of 350–400 °C inside a big reactor is not without its problems.

4.2 The chlorine recycling process—recovering the chlorine from waste PVC

A further project, and one which has similarly not progressed beyond the theoretical stage, has been launched into the recovery of chlorine from waste PVC, such as the PVC from building materials. This project was set up not of necessity but solely on account of the public pressure to which PVC has been subject over the past few years. Using funds contributed by the PVC industry in Germany (AgPU), a project study was compiled by eminent plant builders [22]. This project study relates to an incineration unit with the downstream recovery of chlorine from the flue gases, as is shown in Fig. 11. It was seen, however, that a minimum volume of 80 000 t/year is necessary for the plant to operate on a cost-effective basis. A plant of this type will require an investment of some DM 200 million, and part of this will have to be reflected in the price of the product, together with the operating costs. It is estimated that these latter costs alone will run to > DM 500/t. The other drawback is that, since only small quantities of used PVC will be available in the

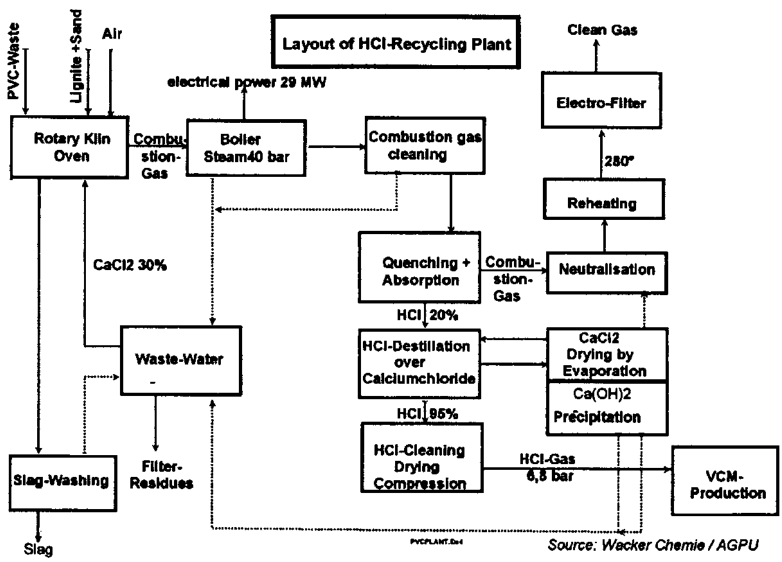


Fig. 11 Layout of HCl-recycling plant.

foreseeable future, the very long transport routes involved will give rise to a further increase in costs.

It is easy to understand that, in view of these cost problems, this project is being scaled-down to a small pilot plant. This is currently being tested for a 20 000 ton plant at the BSL site in Schkopau, East Germany.

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