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Recycled PVC for energy-efficient window profiles: a comprehensive study of thermal and chemical properties

Oumaima Ait khouya[1,2,3], El Hassan Sebbar[3,4], Latifa Elfarissi[2], Najma Laaroussi[4]*

[1] University Hassan II of Casablanca, Laboratory of modeling and simulation of intelligent industrial systems, ENSET Mohammedia, Morocco.
[2] Technical center of plastic and rubber, Casablanca, Morocco
[3] Institute for Research in Solar Energy and New Energies-IRESEN, Morocco
[4]Mohammed V University in Rabat, Material, Energy and Acoustics Team (MEAT), EST Salé, Morocco

Abstract. Recycled polyvinyl chloride (PVC) is increasingly being explored as a substitute for virgin materials in industrial applications, particularly in the production of window profiles. However, the diverse composition of PVC waste, influenced by the presence of additives, impurities, and varying contamination levels, presents a challenge to achieving consistent material properties. This study aims to thoroughly characterize recycled PVC through techniques such as Fourier-transform infrared spectroscopy (FTIR), thermogravimetric analysis (TGA), differential scanning calorimetry (DSC), and inductively coupled plasma (ICP) spectroscopy. The focus is on assessing the physical, chemical, and thermal properties of the recycled material, with a particular emphasis on its thermal insulation performance. By comparing these results with standard specifications and those of virgin PVC, the study provides critical insights into the homogenization process and evaluates the suitability of recycled PVC for high-performance window profiles, offering a promising approach to material reuse in advanced industrial applications.

1 Introduction

PVC is a widely used material due to its long lifespan and excellent mechanical, electrical, chemical, and thermal resistance qualities. The polyvinyl chloride market has grown significantly in recent years and is predicted to grow fast next five years mainly due to the rising demand and economic viability of PVC products. The global production of PVC in 2021 reached 59.14 million tons per year with a production capacity of 54% in Northeast Asia and 17% in North America, followed by Western Europe with a production percentage of 11%[1].

* Corresponding author: oumaima.aitkhouya-etu@etu.univh2c.ma

Fig. 1: PVC market 2022-2027 [2]

Morocco imports almost all of the raw materials used in the processing industry except PVC whose needs are covered by the national electrolysis and petrochemical company SNEP with a percentage of 90%. PVC is one of the most used thermoplastic materials according to worldwide polymer statistics. PVC global demand attended 35 million tons per year. However, the massive number of plastic products generate a huge amount of waste that is being dumped everywhere and creating such environmental issues that the United Nations has identified waste management policies as a top priority to be addressed by governments everywhere. The amount of PVC in waste is directly linked to the level of PVC consumption; as PVC usage increases, the volume of PVC in waste will also rise accordingly. Although the major part of PVC production is converted into long-life products (pipes, window profiles, etc..) a huge part of single use plastic, especially packaging, is accumulated in landfills. Morocco generates 6 million tons of household garbage, which is composed of 70% organic material, 11% plastic, 10% paper, 4% metals, and 5% other elements. In urban areas, 85.2% of garbage is collected, and the great majority is disposed, with a recycling rate of 6% to 10%.[3]
Based on the numbers in the previous sections, a significant proportion of PVC will be transformed into trash that must be recycled in order to protect natural resources, save energy, and reduce greenhouse gas emissions. Recycling encourages a more effective use of resources and a reduction in dependency on raw materials by promoting the circular economy. The market for recycled plastic waste remains limited due to significant barriers around quality, separation of materials, and contamination. In that concern industrials prefer using virgin polymer to ensure high-quality products. While demand for recycled alternatives is growing as sustainability concerns increase, the infrastructure for large-scale, high-quality recycling of post-consumer plastics still needs improvements to address issues around mixed inputs and output quality.
Due to the high chlorine content in PVC, certain recycling methods are not suitable. Specifically, landfilling and composting are not recommended because of the potential risks associated with the oxidative degradation of PVC in the environment. Incineration and pyrolysis may also be discouraged, as they produce large amounts of hydrogen chloride and other toxic by-products. When the source of PVC waste is known, the two permissible recycling methods, mechanical recycling and chemical recycling, are typically chosen.

Mechanical recycling is the primary method used by recycling facilities to process plastic waste and is also widely used in the construction industry. This approach involves physically breaking down the polymer material without destroying the molecular structure through processes like grinding, shredding, and extrusion to produce recycled plastic resins, pellets and flakes, sheets, or films. Mechanical recycling can be conventional, where waste is sorted, ground, and extruded into a recycled product, or non-conventional which utilizes additional chemical processing to separate plastics in mixed or contaminated streams. While conventional mechanical recycling works best for clean, single-polymer waste streams, non-conventional methods use techniques like solvent dissolution or additive compatibility to selectively recover plastics from more complex waste. Thermal processing may also be incorporated to melt and reform thermoplastics, though mixed plastics require compatibilizers to separate polymer types during recycling. Overall, mechanical recycling physically reprocessed plastics at the macro-scale to manufacture recycled products from plastic waste.

Another challenge in mechanical recycling of PVC is the high sensitivity of PVC materials to the environment, which results in constant changes in their morphological structures and characteristics during PVC processing. Because of shear stress during processing, the fusing of plastic particles gradually transforms the original particle structure into a network of entanglements, influencing the material's physical and mechanical characteristics. PVC, in particular, has very poor thermal and light stability and requires the addition of stabilizers to avoid dehydrochlorination and discoloration over its lifetime. Reprocessing PVC waste to produce a recycled material worsens this problem, resulting in a loss in qualities with temperature changes, particularly mechanical features.[4]

Ditta et al.[5] studied the ability of unplasticized PVC (U-PVC) to be processed a number of times. They examined three types of U-PVC: virgin material stabilized with lead, virgin material stabilized with calcium/zinc, and reground 20-year-old post-consumer window profiles. Their findings suggested that, for exterior profiles, the elongation at break does not vary significantly after 20 years of usage compared to new materials. This might be due to the high concentrations of residual stabilizers and other compounds found in these outdoor items. However, various studies have shown that the inherent instability of PVC leads to poorer performance and reduced applicability of the recycled material. A variety of solutions to this problem have been provided, among which two more acceptable techniques involve mixing of the recycled PVC with virgin PVC and/or with other appropriate thermoplastics. Sombatsompop et al.[6] explored the possibility of recycling PVC pipes and examined how the inclusion of recycled pipes affects the rheological, morphological, mechanical, and thermal properties of PVC blends. Their research showed that adding recycled PVC to virgin PVC led to an increase in viscosity and a reduction in the melt flow index. They also observed that as the amount of recycled PVC in the mixture increased, both the hardness and density of the blends rose. Additionally, their findings revealed that the recycled PVC content influenced the glass transition temperature, degradation behavior, and heat deflection temperature of the materials. The incorporation of PVC recycled into different virgin PVC grades depends on the type of grade and properties of interest. An alternative approach to improve recycled PVC properties involves blending it with other thermoplastics, such as acrylonitrile butadiene styrene (ABS) or other styrenic polymers. This can lead to enhanced impact strength and thermal stability. Garcia et al.[7] investigated blends of recycled PVC with ABS, demonstrating partial compatibility attributed to interactions between polar groups. While pure ABS has greater compatibility, mixes containing recycled ABS are more cost effective, while having lower compatibility and mechanical properties. Incorporating styrenic polymers like SAN into the blend also improves the thermal stability of recycled PVC, with variations in mechanical properties depending on the type and origin of the added polymers.

PVC is commonly used in window profiles due to its low thermal conductivity. However, to further enhance the thermal performance, research has explored incorporating insulating materials such as polyurethane foams[8] and aerogels[9][10] into the hollow cavities of the profiles. This approach can significantly improve the overall energy efficiency of the windows.

The effectiveness of such innovations is influenced by the properties of the recycled PVC used. The diversity of waste sources plays a critical role in shaping the characteristics of recycled PVC. Variations in waste composition, including additives, impurities, and contamination levels, can significantly impact the physical, mechanical, and chemical attributes of the recycled material. These factors can alter key properties such as flexibility, strength, and durability, making it challenging to achieve consistent quality. This article focuses on the innovative characterization of recycled PVC, aiming to evaluate its homogenization and compare its properties to standard specifications and those of virgin PVC. The study provides valuable insights into the potential of recycled PVC for industrial applications, addressing the pressing need for sustainable and reliable alternatives in materials development.

2 Characterization of PVC recycled products

Entirely PVC recycled product was provided by MEKSA INDUSTRY. The composition of recycled products was analyzed using Fourier-transform infrared spectroscopy (Perkin Elmer UATR TOW equipment) to identify the functional groups, thermogravimetric analysis (Q500 TA Instrument) determines thermal stability and volatile content, while differential scanning calorimetry (Q 20 TA instruments with intra-cooler RCS) was used to examine phase transitions mainly the glass transition temperature (Tg), offering insights into material rigidity at different temperatures. The environmental hazard was investigated using ICP analysis to control heavy metals content while Gas chromatography coupled mass spectrometry (GC-MS) was carried out to determine phthalate content in recycled products. Integrating these techniques provides a comprehensive characterization of recycled PVC products, ensuring their quality, performance, and compliance with environmental standards.

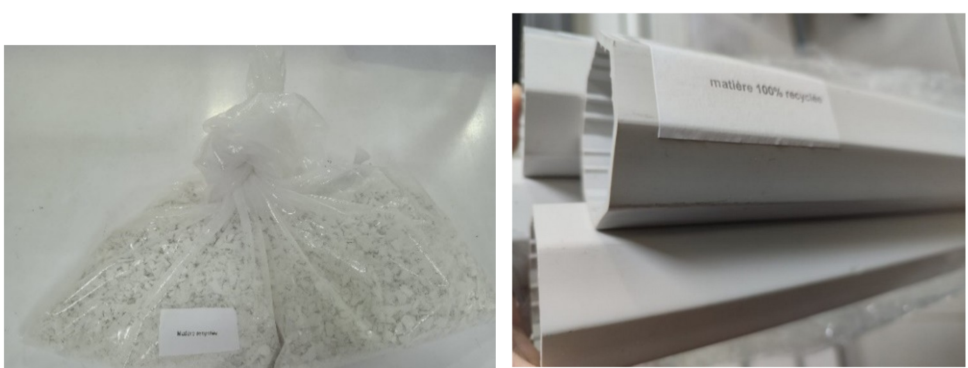

Fig. 2: recycled PVC products

3 Results and discussion

3.1 Determination of the composition of recycled products

Recycled PVC can have different thermal properties compared to virgin PVC due to the presence of impurities or additives. To analyze the composition of recycled PVC profiles, FTIR analysis was carried out (Fig. 2). The Pure PVC and calcium carbonate spectra are given for reference and analysis.

FTIR spectra of recycled products show the presence of Polyvinyl Chloride (PVC) identified by its characteristic peaks of 2911,1254,959,834,616cm^{-1}. The peaks around 2911 cm^{-1} and 1254 cm^{-1} are attributed to C-H stretching and CH rocking respectively while the band around 834 cm^{-1} is designated for C-Cl stretching vibration. Moreover, the FTIR spectra reveal the presence of calcium carbonate identified by its characteristic peaks of 1393, 871, and 712cm^{-1}.[11]

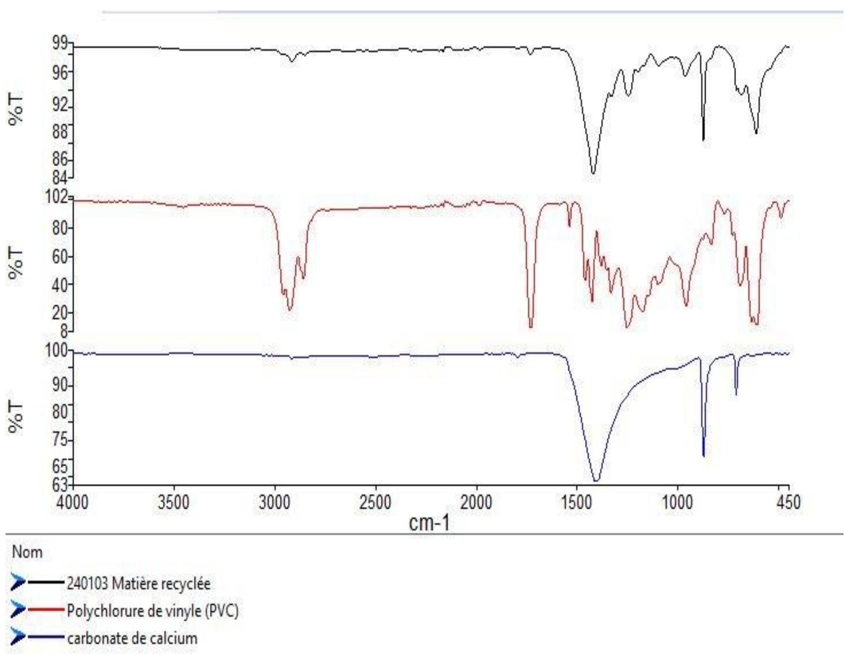

Fig. 3: FTIR analysis of recycled PVC

The glass transition temperature (Tg) of the recycled PVC profile was detected using differential calorimetric analysis (Fig. 8). The DSC curve reveals that the sample has a glass transition at a temperature of 83.4°C, which belongs to unplasticized PVC Tg (80 to 90°C)[12].

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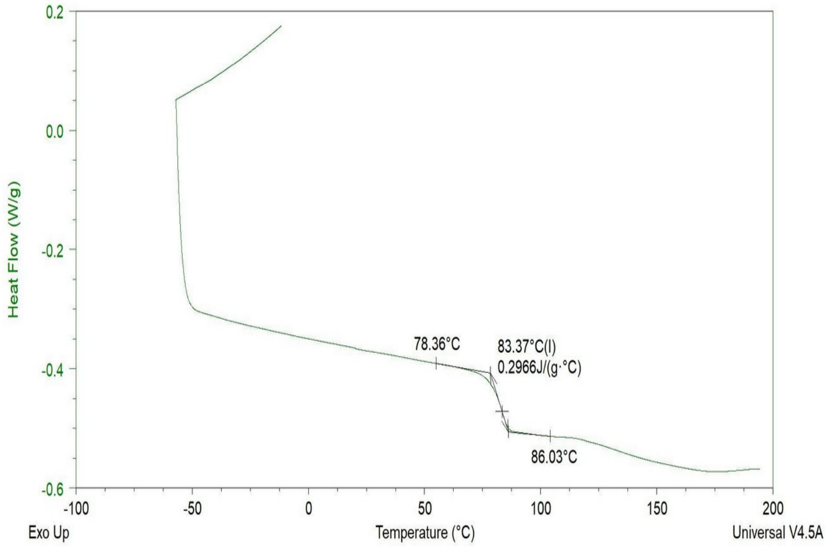

Fig.4: DSC graph of recycled PVC

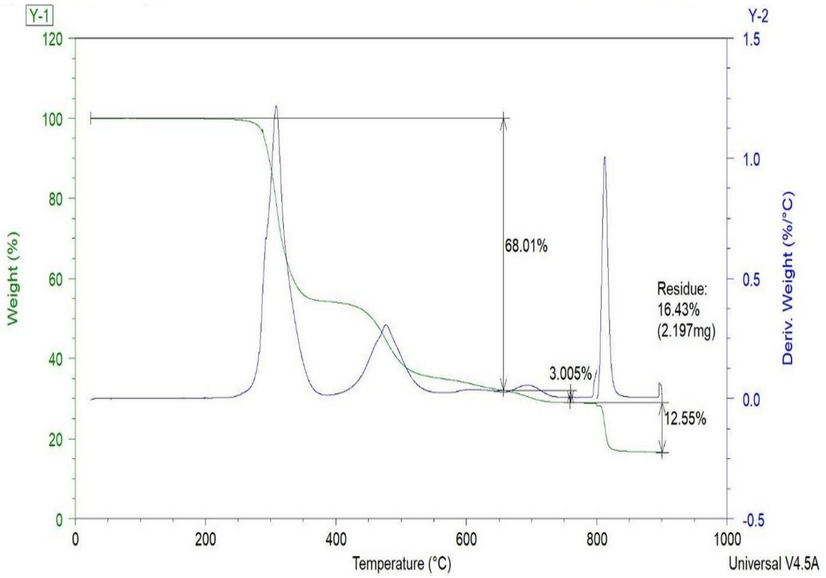

Fig.5: Thermogramme of recycled PVC profile

Thermogravimetric analysis (TGA) is an analytical method used to assess the decomposition and thermal stability of materials, as well as to detect moisture and volatile compounds within a structure by tracking changes in mass. One of PVC's major drawbacks is its tendency to degrade when exposed to heat or UV radiation from sunlight. This issue becomes more severe when chemicals incompatible with PVC are present. The weathering process often results in surface discoloration and reduced flexibility, which eventually leads to increased brittleness and cracking. The TGA thermogram of recycled PVC profile (Fig 9), reveals that the sample has three decompositions. The first weight loss reached its maximum at 308.7°C with a height of 68.0% attributed to the dehydrochlorination of PVC.

The second decomposition at a height of 3.0% and a temperature pic of 693.37°C related to calcium carbonates, and the third decomposition at a height of 12.6% corresponding to the cracking and decomposition of dehydrochlorinated PVC. Finally, a char residue of 16.4% was obtained at the end.
Based on all the mentioned results, it can be concluded that the Recycled material is mainly composed of Polyvinyl Chloride (PVC) at a rate of 80.6%. As well as, a mineral residue of about 19.4%, of which 6.8% is calcium carbonate.

3.2 Determination of phthalates content

Low-molecular-weight plasticizers are a key additive in PVC formulations. While their inclusion reduces certain mechanical properties, such as hardness, tensile strength, and modulus, they significantly enhance low-temperature flexibility, elongation, and ease of processing. The most commonly used phthalates include bis-2-ethylhexyl phthalate (DEHP), diisodecyl phthalate (DIDP), and diisononyl phthalate (DINP). In recent years, DEHP usage has declined, while DIDP and DINP have become more prevalent. The amount of plasticizer added to PVC varies based on the desired characteristics, typically ranging from 15% to 60%, with most flexible applications using between 35% and 40%. [13]
According to the international standards REACH, DINP concentration is limited to 0,1% for toys and childcare articles, it is also restricted for use in materials in contact with foodstuffs[14]. For building sector, in France, construction and decoration products (including products used for wall, floor and ceiling coverings) may only be placed on the market if they emit less than 1 µg/m³ of DEHP and DBP (Order of 30 April 2009 on the conditions for placing on the market construction and decoration products containing carcinogenic substances, mutagenic or reprotoxic category 1 or 2).[15][16]
With the objective of assessing the environmental impact of recycled products, a comprehensive analysis was conducted on ten different phthalates, and the outcomes are detailed in Table 1. The crucial findings reveal that the content of phthalates in the recycled products was consistently below 0.0001%. This result not only signifies a remarkably low concentration of phthalates but also aligns seamlessly with prevailing environmental regulations.

Table 1: phthalates content of recycled PVC product

Specimens	Phthalate content of material by (%)									
	DBP	BBP	DEHP	DNOP	DIBP	DINP	DIDP	DPP	DIHP	DMEP
Ep 1	<LQ	<LQ	<LQ	<LQ	<LQ	<LQ	<LQ	<LQ	<LQ	<LQ
Ep2	<LQ	<LQ	<LQ	<LQ	<LQ	<LQ	<LQ	<LQ	<LQ	<LQ
Ep3	<LQ	<LQ	<LQ	<LQ	<LQ	<LQ	<LQ	<LQ	<LQ	<LQ
Average	<LQ	<LQ	<LQ	<LQ	<LQ	<LQ	<LQ	<LQ	<LQ	<LQ
LQ: Limit of quantification = 1 mg/kg										

3.3 Determination of heavy metals content

Stabilizers play a pivotal role in safeguarding PVC (polyvinyl chloride) from thermal and photochemical degradation, a process vital for preventing catastrophic autocatalytic breakdown. Their primary function involves eliminating hydrogen chloride generated during the degradation process, which, if left unchecked, can lead to severe material deterioration. To effectively fulfill this role, stabilizers must possess both mobility within the polymer at processing temperatures and a rapid reactivity with hydrogen chloride. This necessitates a thoughtful classification into two main categories: primary and secondary stabilizers. Primary stabilizers are characterized by their ability to swiftly migrate to the degradation site within the polymer, where they promptly engage with hydrogen chloride. This interaction results in the formation of stable chemical compounds, ensuring short-term stability for the PVC material. On the other hand, secondary stabilizers, while less mobile, exhibit a remarkable capability to react with a higher concentration of acid. This property makes them particularly effective in conferring long-term stability to the PVC, compensating for their comparatively slower mobility. The synergy between primary and secondary stabilizers often leads to their co-formulation, aiming to harness the distinct advantages of each category. This strategic combination aims to strike a balance, providing both short-term resilience against rapid degradation and long-term protection against sustained acid exposure. In practical terms, typical stabilizers include a range of compounds, such as inorganic lead compounds like trisodium phosphate, metal soaps including calcium, magnesium, barium, or zinc stearates or laureates, metal complexes involving barium, cadmium, and zinc, as well as organostannic stabilizers like dibutyltin diacetate.

Ultimately, this nuanced approach to stabilizer selection and formulation is essential in ensuring the overall stability and durability of PVC materials, especially given the potential environmental and health concerns associated with certain stabilizer compounds, such as lead and cadmium. Therefore, a careful consideration of stabilizer choices becomes paramount in aligning PVC applications with regulatory standards and sustainable practices.[13]

With its RoHS Directive (2002/95/EC), the European Union restricted toxic content in WEEE. The restricted heavy metals include Pb (≤1000 ppm), Hg (≤1000 ppm), Cd (≤100 ppm), and Cr (VI) (≤1000 ppm).

As a result, heavy metal content from stabilizers in the recycled PVC is shown in Table 3. Recycled PVC profile contained low amounts of cadmium inferior to 0.01 mg/kg. while it contains 1.2 mg/kg of chromium, 11.7 of lead and 5,7 of mercury. The concentration of heavy metals in the sample is inferior to the 100 mg/kg maximum limit set by the EU Cadmium Directive.

Table 2: Heavy metals concentration

Element	Concentration in (mg/kg)		
	Specimen 1	specimen 2	Average
Cd	<LQ	<LQ	<LQ
Cr	0.7	1,6	1,2
Hg	4,9	5,7	5,3
Pb	10,9	12,5	11,7
LQ: Limit of quantification =0,01 mg/kg			

4 Conclusion

In conclusion, mechanical recycling emerges as an environmentally friendly and promising solution for managing waste PVC. The findings of this study highlight the viability of producing high-quality products using 100% recycled PVC waste profiles. This suggests that replacing virgin PVC with recycled PVC waste can lead to significant reductions in environmental impact. This approach presents a sustainable and economically feasible solution for both the construction and waste management industries.

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