Comparison of mechanical and thermal characteristics of PVC and recycled PVC used in window frames

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Abstract: Improving the energy efficiency of buildings is a major challenge for reducing energy consumption and mitigating environmental impact. As key elements of building envelopes, windows play a crucial role in thermal management, capturing natural light and maintaining interior comfort. However, they also contribute significantly to heat loss from buildings. This article focuses on recent advances in the field of windows, with particular emphasis on the mechanical and thermal characterization of PVC and recycled PVC profiles. The results obtained show that PVC and recycled PVC profiles offer notable mechanical strength and good heat resistance, as evidenced by a softening temperature of 80.55°C and heat reversion percentages in line with standards. Recycled PVC boasts superior dimensional stability with a thermal reversion of 0.5%, suggesting robust performance even in environments subject to temperature fluctuations. However, to achieve optimum performance, particularly in terms of mechanical strength, it is essential to further optimize the formulation and production process, especially for recycled PVC.

Keywords: Window frame performance, Mechanical and thermal characterization, PVC profiles

1 Introduction

Polyvinyl chloride (PVC) is a polymer material widely used in a variety of industries, including the manufacture of profiles for windows, doors, and other building components. Its popularity lies in its mechanical properties, resistance to thermal deformation, and durability under varying environmental conditions. However, with growing environmental concerns, PVC recycling has become a major issue in reducing the ecological footprint and promoting a circular economy. To mitigate energy gains or losses, various glazing configurations have been developed in response to climatic requirements. Today, a variety of alternative window technologies are available. These include windows equipped with low-emissivity glass **[1]**, reflective lenses **[2]**, glazing with solar control film **[3]**, windows integrating the use and adaptation of blinds **[4]**, and the use of multiple glazing **[5]**. These always consist of two, three, or even more sheets of glass, separated by spaces forming elongated cavities. Some researchers have introduced air or absorbent gases or even created a vacuum between these glass layers. In addition, the use of aerogels **[6]**, phase-change materials **[7]**, thermochromic glazing **[8]**, and thermotropic **[9]**, has been explored to prevent heat gain and/or loss.
The use of recycled PVC in windows represents a major advance towards sustainable construction, combining performance, economy, and respect for the environment. This introduction highlights the key research supporting the integration of recycled PVC into the window industry while acknowledging the technical challenges that remain to be overcome to maximize its benefits.
In this study, we examined the mechanical and thermal performance of virgin and recycled PVC profiles. Tensile strength, Vicat softening temperature, and thermal reversion tests were carried out by international standards, in particular EN 12608-1 **[10]** in conformity with international standards specifications and test methods.

2 Characterization of the PVC profile

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2.1 Determination of tensile strength

In a tensile strength test, a sample of the PVC profile is placed in a testing machine and subjected to a tensile load until it breaks. The test determines the maximum stress a sample can withstand before breaking, as well as the amount of elongation or deformation that occurs before failure. These measurements can provide useful information on material strength and ductility and can be used to optimize the design and manufacture of PVC profiles.
The tensile strength of the PVC profile was measured on the exposed outer wall of the specimens by ISO 527 **[11],** applying a test machine-driven clamp displacement speed of (10 ± 1) mm/min (see **Fig. 1**).

Fig. 1: Tensile test machine

Five test specimens were evaluated, the results are shown in the **table 1**. The obtained tensile strength, measured at 38.9 MPa, demonstrates a robust mechanical resistance of the material. This value suggests that the PVC profile can withstand significant loads before reaching the breaking point.

Table 1: Tensile test results

Sample	Thickness (mm)	Width (mm)	Breaking force (N)	Fracture stress (MPa)
1	2.30	9.9	922.	40.5
2	2.61	10.5	1036.5	37.8
3	2.40	10.3	909.5	36.8
4	2.40	10.3	901.1	36.5
5	2.65	9.4	1069.5	42.9
Average			1020	38.9
Typical deviation			40.71	2.7

2.2 Determination of heat reversion

Heat reversion is a measure of PVC-U's (unplasticized polyvinyl chloride) capacity to maintain form and dimensional integrity when exposed to high temperatures. Heat reversion for PVC-U refers to the proportion of the material's initial deformation that persists after some time at a temperature of 100°C (212°F).
According to NM EN 12608-1 **[10].** the heat reversion of the PVC-U profile should be measured in compliance with EN 479 **[12].** For that. a specimen of 250 mm was prepared by tracing two axes with a distance of 200 mm so that each one is approximately 25 mm from one end of the test specimen (see **Fig. 2**). Then. the sample was placed in the oven at 100°C for 60 min. At the end of the test. the sample was kept in a conditioned laboratory (23°C) to cool down before measuring the distance between the marks. The heat reversion was calculated using this Formula:

$$R = \frac{\Delta L}{L} \times 100 \quad (1)$$

Where:
$\Delta L = L_0 - L_1$;
L_0: The distance between the marks before heating in the oven in millimeters.
L_1: The distance between the marks after heating in the oven in millimeters.

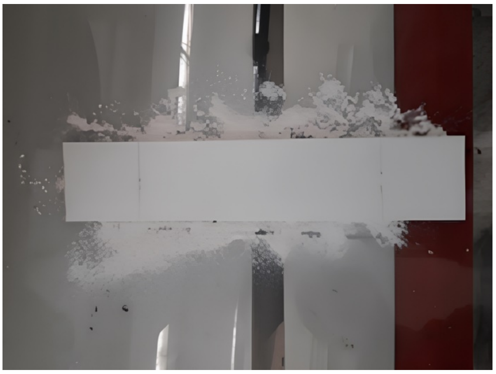

Fig. 2: Test sample for heat reversion at 100°C

lower heat reversion percentage indicates better heat resistance and dimensional stability of the PVC-U material. which is important for applications where temperature fluctuations may occur. According to NM EN 12608-1**[10].** the test specimen the heat reversion of the two largest opposing sight surfaces should be inferior to 2% (see **table 2**). As a result. the heat reversion value of the analyzed profile sample was 1.9 % which matches the standard specifications.

Table 2: Heat reversion result

Sample	L_0 (mm)	L (mm)	V_L (mm)	R_L (%)
1	200.75	197.00	3.75	1.87
2	200.50	197.25	3.25	1.62
3	200.75	196.25	4.50	2.24
			Average	1.91
			Typical deviation	0..31

2.3 Vicat softening temperature

The softening temperature of PVC profiles can be determined by performing a Vicat test. which is an essential indicator of their general quality and suitability for use in different applications. The test entails detecting the depth to which a needle penetrates the PVC sample at a given temperature. and it can be used to assess the material's resistance to deformation. which is important in situations where temperature fluctuations are prevalent.
According to NM ISO 306 **[13]** the test was done using three specimens immersed in a silicone oil as illustrated below (**Fig. 3**).

Fig. 3: Vicat analysis

The results showed that the material has a softening temperature average of 80.55 °C. According to EN 12608-1**[10].** the average Vicat softening temperature shall be superior to 75°C and each value shall be greater than 73°C. which fits with the obtained results (see **table 3**).

Table 3: Vicat test results

Sample	Softening temperature VICAT (°C)
1	80.3
2	80.6
Average	80.5
Typical deviation	0.21

3 Characterization of recycled PVC profiles

3.1 Determination of tensile properties

Under laboratory conditions. the tensile test was carried out according to the standard ISO 527 **[11]** applying a rate of displacement of the driven grip of the test machine of (10 ± 1) mm/min.
The obtained tensile strength (**Table 4**). average is 42.34 MPa. demonstrates a robust mechanical resistance of the material. This value suggests that the recycled PVC material can withstand significant loads before reaching the breaking point as well as good ductility. indicating the material's capacity to undergo substantial deformation before yielding. Compared to the literature. PVC-U typically demonstrates a tensile strength in the range of 50- 75 MPa. which is notably higher than our findings. This underscores the importance of carefully formulating PVC foam to ensure its mechanical strength. Deviations from the expected tensile strength in PVC-U indicate the need for adjustments in the foam formulation process to guarantee the desired mechanical robustness. emphasizing the importance of a meticulous approach in achieving optimal performance.

Table 4: tensile test results

N°	Thickness (mm)	Width (mm)	Breaking force (N)	Stress at break (N/mm^2)
1	2.4	10.6	1125.2	44.2
2	2.4	10.8	1033.2	39.9
3	2.5	10.8	1094.5	40.5
4	2.4	10.3	1082.1	43.8
5	2.4	10.3	1070.5	43.3
Average			1081.1	42.34
Standard deviation			33.7	2.0

3.2 Vicat softening temperature

The Vicat test entails detecting the depth to which a needle penetrates the PVC sample at a given temperature. and it can be used to assess the material's resistance to deformation. which is important in situations where temperature fluctuations are prevalent.
According to NM ISO 306. the test was done using three specimens which are immersed in a silicone oil. The results (see **table 5**). showed that the material has a softening temperature average of 80.55°C which is in accordance with EN 12608-1**[10].** The standard specifications require that the average Vicat softening temperature shall be superior to 75°C and each value shall be greater than 73°C. which fits with the obtained results.

Table 5: Vicat test results

Specimen	VICAT Softening Temperature (°C)
1	80.9
2	80.9
The average	80.9
Standard deviation	0.21

3.3 Determination of heat reversion

The Pipe Longitudinal Reversion Test, also known as the heat reversion test for PVC-U refers to the proportion of the material's initial deformation that persists after some time at a temperature of 100°C (212°F)(see **Fig.4**).
According to EN12608-1**[10].** the heat reversion of the PVC-U profile should be measured in compliance with EN 479. For that. a specimen of 250 mm was prepared by tracing two axes with a distance of 200 mm so that each one is approximately 25 mm from one end of the test specimen. Then. the sample was placed in the oven at 100°C for 60 min. At the end of the test. the sample was kept in a conditioned laboratory (23°C) to cool down before measuring the distance between the marks. The heat reversion was calculated using **Equ. (1**).

Fig. 4: Drying the profiles

Lower heat reversion percentage indicates better heat resistance and dimensional stability of the PVC-U material. which is important for applications where temperature fluctuations may occur. According to EN12608-1**[10].** the test specimen the heat reversion of the two largest opposing sight surfaces should be inferior to 2% (see **table 6**). As a result. the heat reversion value of the analyzed pre-consumption PVC waste sample was 0.5 %. which matches the standard specifications.

Table 6: heat reversion test results

N°	L0 (mm)	L (mm)	VL (mm)	RL (%)
1	200.50	199.50	1.00	0.50
2	200.75	199.75	1.00	0.50
3	200.25	196.25	1.00	0.50
Average				0.50
Standard deviation				0.00

4 Conclusion

The results reveal that PVC and recycled PVC profiles offer appreciable mechanical strength. with tensile strength values of 38.9 MPa for standard PVC and 42.34 MPa for recycled PVC. Concerning heat resistance. softening temperature tests showed satisfactory performance. with an average temperature of 80.55°C for both types of profile. exceeding the 75°C threshold required by EN 12608-1**[10].** These results confirm the materials' good resistance to thermal deformation. making them suitable for a variety of applications. even under fluctuating temperature conditions.
Finally. thermal reversion tests revealed excellent dimensional stability. particularly for recycled PVC. which showed a thermal reversion of 0.5%. compared with 1.9% for virgin PVC. These values. both below the 2% threshold required by the standard. indicate that both virgin and recycled PVC profiles possess satisfactory thermal robustness. In short. although recycled PVC shows slightly lower performance in terms of mechanical strength. it excels in thermal stability. making it a viable material for demanding applications.

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