

The Viability of Using Different Types of Recycled Plastic as Glazing in Windows

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Abstract

Plastic waste is a growing issue that needs to be addressed, multiple solutions are established to reduce its impact on the environment. The aim of this research is to make use of the plastic waste piling up and, at the same time, to create a convenient daylighting solution. The research proposes a sustainable fenestration system to be used in hot-arid climates, particularly in Egypt, where it is common to use tinted glass to lower the heat gain. First, a recycling process was carried out to create samples, the samples were then tested to obtain their optical properties and lastly Radiance, a daylighting simulation tool, was used to test the performance of recycled plastics as a window glazing material. In the recycling process, three plastic types were used to create the samples: polypropylene PP (number 5), polystyrene PS (number 6), and polycarbonate PC (number 7). It was concluded that the use of recycled plastics as a glazing material is indeed possible. Polycarbonate ranked as the most transparent, yet its impurities were the most visible. Polystyrene was also observed to be quite transparent, however its transparency was inversely related to its thickness. Polypropylene was the least transparent under the selected settings. Nonetheless, further research is required regarding the recycling process settings, to determine the possibility of obtaining more transparent results.

1. Introduction

Daylighting is one of the major indoor environmental aspects that has a major influence on the behaviour and attitude of the occupants (Cuttle, 1983). Daylighting is used as one of the effective passive strategies to uniform illumination within living spaces, where high energy savings can be achieved (Lim et al., 2012). It is a major factor in human health

and productivity that has a positive effect on the psychological comfort more than artificial lighting (Cheung and Chung, 2008; Cuttle, 1983). Nevertheless, daylighting is hard to fully exploit due to the challenges that accompany it, like excessive heat gain or the need for complex expensive strategies to introduce it adequately into the space. Consequently, daylighting benefits are often overlooked in Egypt as most common practices favor the small fenestration area, which hardly allows an adequate daylighting distribution. For instance, according to the Egyptian Energy Code 306-2005 (2006) a window-to-wall ratio that exceeds 30 % is unacceptable, a rather insufficient value for deep spaces. Moreover, very few daylighting techniques utilize passive strategies that don't require the use of virgin materials.

Egypt produces around 980,000 tons of plastic waste annually (2005/2006) while only 30 % gets recycled and 5 % is reused. The remaining 65 % is either burnt or buried unused (Plastic Technology Center, 2008).

This paper proposes a sustainable Fenestration System with a translucent glazing that makes use of the accumulating plastic waste and serves as a convenient means to utilize daylighting as well. The translucent layer will be made of recycled plastics, such as polypropylene PP (number 5), polystyrene PS (number 6), and polycarbonate PC (number 7). PC is considerably used in construction projects for semi-transparent roof tiles, therefore, considered fairly expensive compared to other types of plastics. PP is the main kind of plastic for food containers that comes in different colours, transparencies, and optical properties. PS is also used in the food sector, however, more disposable than PP and less cheap.

Polystyrene products consist of a very high percentage of air gaps in between their structure, therefore they are considered light. The recycled plastic layer will diffuse the light transmitted into the room in order to prevent bright spots near the window. At the same time, this will ensure privacy to users inside the space as well as adequate daylighting.

2. Literature Review

2.1 Recycle Plastic Usage

Recycled plastics have numerous uses in the building industry. Aminudin et al. (2011) reviewed the potential use of recycled expanded polystyrene (EPS) as a thermally insulating material in buildings. Aminudin et al. also stated that EPS has high compressive stress, which makes it suitable for integrating with building materials.

In an extensive literature review Lei Gu and Togay (2016) stated that plastics such as Polyethylene terephthalate (PET), EPS, high-density polyethylene (HDPE) and low-density polyethylene (LDPE) can be recycled and used as plastic aggregates, while PP and PET fibres can be used as plastic fibres, and both Polyamide (PA) and Phenol formaldehyde (PF) are used in concrete in different ratios and weights, since they give different properties to the concrete mix.

Recently, Dalhat and Al-Abdul Wahab (2016) formulated a cement-less and asphalt-less concrete mix using recycled plastic such as recycled PP and recycled HDPE.

Yet, no cited research mentioned the use of recycled plastic as a glazing in a fenestration system, and a few researchers mentioned the optical properties of recycled plastics to be used for glazing.

2.2 Glazing Technologies

Glazing systems went through several improvements since the beginning of the 20th century, from the introduction of the double and triple pane glass to the creation of tinted and Low-E glass. In his paper entitled "Solar Radiation Glazing Factors for Window panes, Glass Structures and Electrochromic Windows in Buildings—Measurement and Calculation" Bjørn Petter Jelle (2013) summarized

the state of the art technologies in glazing systems. He specifically focused on Electro Chromatic Windows (ECW), which are dynamic window structures that vary in voltage according to the solar radiation, thus changing the window's color and tint. In "The Role of Window Glazing on Daylighting and Energy Saving in Buildings" Hee et al. (2015) compared the performance of single, double, and triple glazing windows thermally and visually.

2.3 Glass Properties and Use in CFS

One of the windows' main design parameters, with regard to visual properties, is the visible transmittance (T_{vis}), which ranges from 0 to 1.0. When it approaches 1.0 it means that the material transfers more light energy when light passes through (Lawrence Berkley National Laboratories, 2015). Another main property is the transparency of the material, defined as the amount of perception of an object within or at the other side of any material. When light is transmitted without the clarity of the image this is called "translucency" (Tripathi, 2002). Last but not least, the refraction index is a vital optical property of any material which controls the refraction angle of any incident light on a material, furthermore the total internal reflection of the material (TIR) is determined by the value of the refraction index. As the refractive index value is higher, a higher refraction angle occurs as light propagates through the material.

3. Methodology

The process of manufacturing and selecting the suitable recycled plastic included several steps which are categorized as experimental physical work and simulation and validation work. The experimental work involves recycling plastic products and testing the optical properties of the final recycling output. While the simulation work engages with the optical properties and incorporates them in a Radiance-based simulation to test the daylight performance of the materials.

3.1 Recycling Plastic Material Manufacturing Process and Optical Property Testing

A suitable plastic material was selected by testing different alternatives, and visually observe the optical properties of the products. The plastic types included Polycarbonate PC, Polypropylene PP and Polystyrene PS in this paper. The 3 materials were bought as post-consumer products and a recycling process was carried out. First the materials were cleaned then shredded using a shredding machine. The shredded plastic underwent another refined shredding process in order to reach fine pellets of the material.

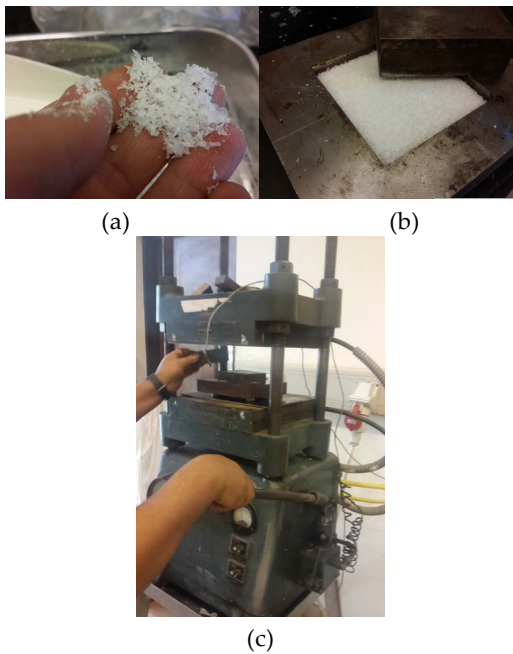


Fig. 1 – (a) Fine pellets of PS shredded (b) Pellets inserted between two plates (c) Hydraulic press machine with heaters

The fine pellets were inserted between two plates as shown in Fig. 1. Afterward, the dyes were placed on a hydraulic press with heaters installed on the upper and lower plates. Different pressures and temperatures were tested for each material, in order to reach an acceptable range of optimum settings as shown in Table 1. The final product dimensions were 10 cm x 10 cm, and 4 mm thickness.

The successful products were optically tested using a UV/VIS spectrometer to measure the optical properties of the material such as the transmission and reflectance.

Table 1 – Settings for recycling different types of plastics

Material	Temperature (°C)	Pressure (psi)
PC	150-170	2000
PS	105-110	1500
PP	120-140	2000

3.2 Daylight Simulation Software: Radiance

After manufacturing and testing different recycled plastics, they were simulated on Radiance, a light simulation software to ensure viability before manufacturing an actual prototype.

Radiance simulates prismatic designs with variable outputs, dependent on the input angle, using the BSDF. The BSDF is generated by creating an accurate geometrical 3-dimensional model, also the material is modelled on Radiance using flexible material definitions. To model a translucent plastic material on Radiance the *trans* definition is used. However, it is highly probable that the recycling process would not be 100 % pure homogenous plastic. Any type of impurities will affect the optical properties of the final product. The impurities are randomly present within the medium of the panel. Therefore, to represent those impurities during the simulation the prismatic panel material should contain a *Function File* replicating those impurities. The most suitable function file done in radiance for the previous circumstances is the *Noise.cal*. In order to use the *Noise.cal* function file, another material definition should be used. The *transfunc* is a unique material definition script that is used for arbitrary Bidirectional Reflection Distribution Function (BRDF). The arguments to this material are the data file, in this case, the *Noise.cal*, and coordinate index functions in addition to specular transmission and reflectance. The only modifier that is not available in this material definition is roughness, which is not required since the BRDF data is dominant. The *transfunc* parameters is defined as follows:

<i>modifier</i>	<i>transfunc</i>	<i>identifier</i>
2+	<i>brtd</i>	<i>funcfile</i>
0		
6	<i>R</i>	<i>G</i>
	<i>rspec</i>	<i>B</i>
	<i>trans</i>	◀(Colour)
		◀(specularity)
	<i>tspec</i>	◀(transmission
		& transmitted specularity)

The BSDF is created using genBSDF and afterwards tested using Radiance’s latest 5-phase method. The 5-phase method is considered an effective method for performing annual simulations of complex fenestration systems (CFS) and dynamic fenestration systems. The flux transfer is categorized into 3 independent simulation stages as the following:

1. Sky dome to the exterior of fenestration
2. Transmission by BSDF through fenestration
3. Interior of fenestration into the simulated room

The space design used to test the proposed design is a standard office room by Reinhart et al. (2013) used for daylighting and illumination. The test was conducted in Cairo, Egypt, a hot arid area, with clear sky conditions throughout the year.

Table 2 – Simulation settings for Radiance

Interior Room Surface	Parameter	Value
Interior Walls	Reflectance (%)	0.50
Floor		0.50
Ceiling		0.80
Window Frame		0.50
Window/wall ratio	Ratio (%)	0.20
Windows Dimensions	Length x Width (m)	2.0 x 1.8
Shading Device	Y/N	No
Illuminance sensor point	Height (m)	0.75
	Distance in-between (m)	0.50
	Number of points	45
	Distribution (L x W)	8 x 5
Sky Condition	Clear/Overcast/uniform	Clear Sky

To obtain accurate and comparable results for an annual simulation, it is recommended to use the state-of-the-art measurement method. The Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) are 2 factors lately published by the US Illuminating Engineering Society in the LM-83-12 document “Approved Method: IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE)” (IES, 2013). The sDA describes “the percentage of floor area that receives at least 300 lx for at

least 50 % of the annual occupied hours”. Specifically, ASE measures “the percentage of floor area that receives at least 1000 lx for at least 250 occupied hours per year”. Combining both measurements gives an indication of daylighting adequacy and visual comfort (IES, 2013).

4. Results and Discussion

4.1 Optical Properties and Visual Observations of Different Recycled Plastic Materials

Visual Observation of the different recycled materials: First, the samples were visually observed. All 3 materials are translucent but with different grades. The polycarbonate is the most transparent, visually, while the polypropylene is hardly transparent. Yet, it can transmit some light. Both polycarbonate and polystyrene developed a brownish colour; however, polypropylene developed a white colour.

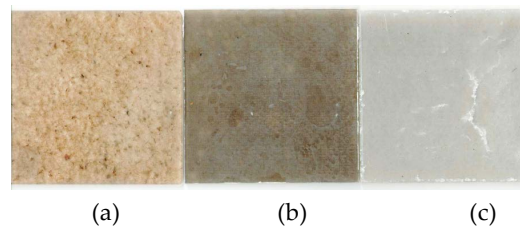


Fig. 2 – The recycled plastic samples (a) PC (b) PS (c) PP

The polycarbonate visual texture indicates the presence of high impurities and incomplete mixing of the polycarbonate pellets. However, polystyrene had a clearer texture with little impurities to see. On the other hand, polypropylene showed some vine-like impurities which resulted from “un-cooked” PP particles.

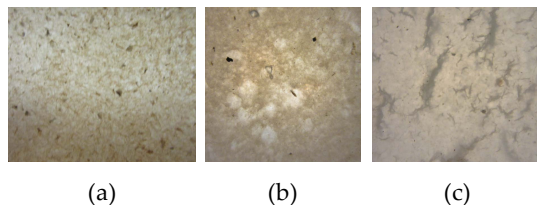


Fig. 3 – Close-up of the 3 materials (a) PC (b) PS (c) PP

Diffused Transmission Measurements:

The spectrophotometer results at 550 nm are shown as follows:

Table 3 – Diffused and specular transmittance and reflectance of the different plastics

Material	Transmittance		Reflectance	
	Diffused	Specular	Diffused	Specular
RPC	8.6 %	20.0 %	34.0 %	37.4 %
RPS	2.5 %	2.8 %	45.1 %	49.6 %
RPP	2.2 %	2.4 %	45.5 %	50.0 %

The previous findings resulted from the average values of the material along different points on the surface since recycled plastic is impure and contains different foreign particles within the medium of the material. Those impurities would affect the overall light transmission of the material.

4.2 Radiance Simulation Results of the Different Recycled Plastic Materials

The readings from the spectrophotometer were used in the material definition in Radiance in order to accurately model the behaviour of the materials selected along the whole year using the five-phase method. The rPC material was chosen for comparison and was modelled with *trans* where the diffused and specular transmission and reflection were converted to Radiance’s *trans* material definitions.

```
void      transfunc      FlatGlass
2        brtd      noise.cal
0
6        0.672  0.672  0.672
         0.370
         0.286  0.20
```

As for the Radiance simulation, the recycled PC samples resulted in decreasing the direct illumination in front of the window in comparison with the ordinary tinted glass of the same transparency; however, the illumination also decreased in the whole room due to the decrease in total transmission of the sample.

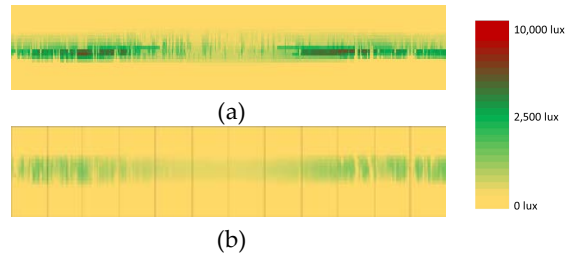


Fig. 4 – Total hourly illuminance in lux for 1 year at the node near the window (a) Tinted glass (b) Recycled Polycarbonate

As for the sDA and ASE, there was a decrease in the total values of both measurements, which means that less direct daylighting has entered the space. The sDA decreased from 40 % to 22 % whereas the ASE decreased from 33 % to 18 %.

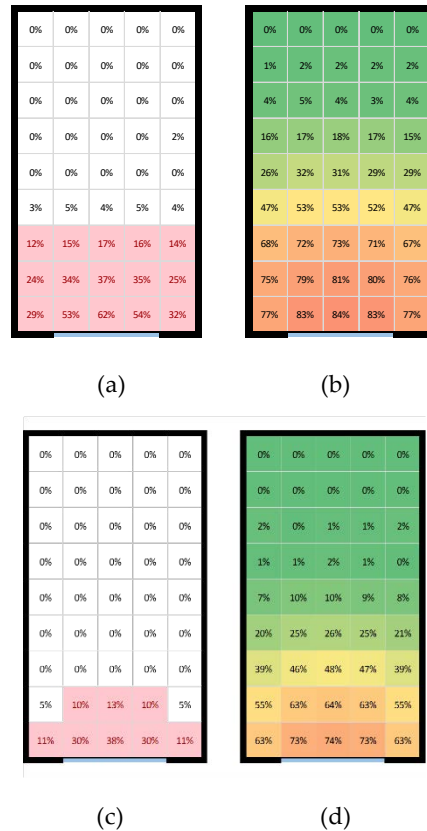


Fig. 5 – ASE (left) and sDA (right) for both Tinted glass (a,b) and recycled PC (c,d)

5. Conclusions

The idea of using recycled plastic as a glazing part in the window is feasible, and its texture and visual appearance could serve as a tinted glazing material. However, further modifications in the recycling

process and proper treatments are needed. Polycarbonate has the highest transparency yet its impurities are the most visible. While polystyrene might have greater potential in achieving greater transparency either by decreasing the thickness or enhancing the recycling process. As for polypropylene, further research has to be done on the right settings and smaller thicknesses should be tested since it has the potential of creating white and translucent glazing. On the other hand, further tests should take place to analyze the material's thermal properties, such as the U-value, and physical properties to ensure that the recycle plastic will withstand internal and external changes in the environment. A wider variety of plastics should be tested, as well as different mixtures of plastics.

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