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Comparative Analysis of Compression Molded Products of Recycled Waste Poly(Vinyl Chloride) and Virgin Poly(Vinyl Chloride) Fill Material

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Highlights:

- Waste poly(vinyl chloride) fill from cooling tower of a power plant was collected and recycled into recyclates.
- Compression molded product of waste PVC was prepared using the recyclates at optimized conditions.
- Compression molded product of virgin PVC was prepared and the waste PVC product and the virgin PVC product were evaluated by comparative analyses.
- ATR-FTIR characterization revealed that the chemical structure of the waste PVC did not degrade during re-melting and re-processing.
- Tensile and thermal properties showed that the waste PVC did not lose its tensile strength and thermal stability during re-melting and re-processing.

Abstract. Waste poly(vinyl chloride) fill material from the cooling tower of a power plant was used for mechanical recycling. Mechanical recycling is the processing of plastic waste without changing the original chemical structure of the plastic. The waste rigid poly(vinyl chloride) fill material was cleaned, grinded and compression molded at optimized conditions of time, temperature and pressure using a compression molding machine. Virgin poly(vinyl chloride) was purchased and compression molded by the same compression molding machine. The compression molded sheets of waste poly(vinyl chloride) and virgin poly(vinyl chloride) were characterized by attenuated total reflection Fourier transform infrared analyses, tensile properties analyses, and thermal properties analyses. The results revealed that waste rigid poly(vinyl chloride) fill material is mechanically recyclable into new products such as pipes, profiles, furniture and other related products.

Keywords: *compression molding; mechanical recycling; tensile properties; thermal properties; waste poly(vinyl chloride) fill material.*

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1 Introduction

Recycling is an essential tool to achieve a sustainable plastics economy, environmentally as well economically, due to increasing environmental pollution entering into the oceans and land, coupled with micro and nanoplastic pollution that has an uncertain impact on human and ecosystem health in all natural system environments [1,2]. In the current scenario, plastic waste consumption is increasing day by day, while it is very difficult to manage plastic waste [3]. Methodologies for reutilization of plastic waste are recycling, landfill, incineration, gasification, hydrogenation, etc. [3]. Mechanical recycling is the best-known method, which includes injection molding, extrusion, rotational molding, and heat pressing. Only thermoplastic polymers, such as polypropylene (PP), polyethylene (PE), polyethylene terephthalate (PET), and poly(vinyl chloride) (PVC), can normally be mechanically recycled [4]. Thermoplastic polymers have unique properties (physical, thermal and electrical) that make them suitable for a wide range of applications because they are light-weight, inexpensive and durable. These polymers are recyclable as they can be re-melted and reprocessed into end products [5]. Thermoplastics account for roughly 80% of the total plastic consumption.

Annual waste analysis is based on plastic waste in different waste streams [6]. Most of the recycling of PVC products occurs in the form of PVC plates, pipes, rods, films, and sheets for construction and civil engineering applications [7]. Soft-PVC products account for about 37% of all PVC products, such as PVC film, flexible pipes, footwear, bags, clothing, etc., while hard-PVC products account for about 52% of all PVC products, such as rainwater gutters, pipes, profiles, furniture, etc.[7-8]. PVC polymers are linear and strong and are produced by the polymerization of vinyl chloride monomers. They consist for 57% of chlorine and 43% of carbon. Pyrolysis is a common plastic recycling technique used to convert plastic waste into energy sources in the form of solid, liquid and gaseous fuels [9]. However, highly toxic and corrosive hydrogen chloride (HCl) is released during pyrolysis of PVC, which can pose a threat to the environment and humans and can damage the pyrolysis installation [8]. Therefore, in this research, waste PVC fill material from a power plant was used for mechanical recycling. This rigid PVC fill material is used in the cooling systems of different types of industries and rejected as waste after a few years. Waste PVC can be utilized to make value added products such as composite materials and other industrial products.

In this work, waste poly(vinyl chloride) fill material from a power plant was used to make recycled compression molded product. The comparative ATR-FTIR, tensile and thermal properties of compression molded products made from waste PVC and virgin PVC were investigated.

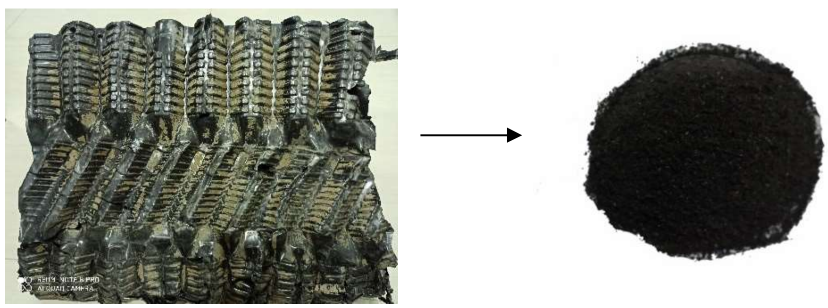
2 Experimental Method

2.1 Materials

Waste rigid PVC fill material from the cooling tower of a power plant were collected from Haripur Power Plant, Narayongonj. Virgin PVC (Nasir PVC) was purchased from Nasir Group of Industries, Bangladesh.

2.2 Cleaning and Grinding of Waste PVC Fill Materials

The waste PVC was cleaned thoroughly with warm water and detergent and finally with distilled water. It was dried and shredded into pieces and then grinded in a grinder.



(a) (b)

Figure 1 (a) Waste poly(vinyl chloride) fill material from the cooling tower of a power plant and (b) its cleaned granular recyclate.

2.3 Preparation of Compression Molded Sheets of Waste PVC and Virgin PVC

The dried waste PVC granules were put into a mold and placed in a compression molding machine (Paul-Otto Weber Press Machine, Germany). Pressure, temperature, heating time and cooling time were optimized to prepare a compression molded sheet of waste PVC. The waste PVC sheet was made at a molding temperature of 185°C, applied pressure of 200 to 250 kN, and heating time of 12 minutes. After completion of heating, an additional pressure of 50 kN was applied to make the samples free of voids. Tap water was circulated through the outer area of the heating plates of the machine to cool and cure the samples. Finally, the compression molded sheet was taken out of the mold and cut into specimens of suitable dimensions for testing. All the compression molded sheet samples and different types of testing specimens of waste PVC and virgin PVC were made under the same conditions. In this research, compression molded product was made using recyclates of waste PVC. Compression molded product of virgin PVC was also made to compare with the waste PVC by ATR-FTIR analyses, tensile properties analyses and thermal properties analyses.

2.4 Attenuated Total Reflection-Fourier Transform Infrared (ATR-FTIR) Analysis of Waste PVC and Virgin PVC

The compression molded sheets made from waste PVC and virgin PVC were used to take ATR-FTIR spectra using an ATR-FTIR spectrophotometer (Perkin Elmer Frontier FTIR/NIR Spectrophotometer).

2.5 Tensile Properties Analyses of Waste PVC and Virgin PVC

The compression molded sheets made from waste PVC and virgin PVC were used to analyze the tensile properties using a Universal Testing Machine (model 1410-Titan[5], load cell 5000N, UK) at a cross head speed of 15 mm/min. The ASTM D 3039/D 3039M-00 (2002) method was followed to conduct the tensile testing [10].

2.6 Thermal Properties Analyses of Waste PVC and Virgin PVC

Thermogravimetric analyses (TGA) of the compression molded sheets of waste PVC and virgin PVC were carried out using TG-GC-MS (Pyris-Clarus 680-Clarus SQ8, PerkinElmer, USA) at a heating rate of 15 °C/min under nitrogen atmosphere from 40 °C to 850 °C.

2.7 Specific Gravity and Water Absorption Test of Waste PVC and Virgin PVC

Specific gravity and water absorption of the compression molded waste PVC and compression molded virgin PVC were measured. Specific gravity was measured following the ASTM Standard D 792-13 method [11] and water absorption was measured following the ASTM Standard D 570-98 method [12]. Water absorption testing of the PVC samples was done by immersing the samples in boiling water for about 2 hours as described in ASTM D 570-98.

3 Results and Discussion

3.1 Compression Molded Product of Waste PVC and Virgin PVC

The waste PVC fill material from the cooling tower of a power plant consisted of a rigid PVC polymer. This had been used as filler material in the cooling system of a power plant and rejected as waste PVC after four years. The waste PVC fill material was cleaned, shredded and grinded into recyclates (smaller particles).

Such recyclates of waste PVC can be re-melted and remolded into different products.

3.2 ATR-FTIR Characterization of Waste PVC and Virgin PVC

Comparative ATR-FTIR spectroscopic analyses of waste PVC and virgin PVC were conducted to characterize the chemical structure of the waste PVC and its compression molded product. The spectra of the waste PVC, the virgin PVC, the compression molded waste PVC, and the compression molded virgin PVC are presented in Figure 2 and Table 1 respectively.

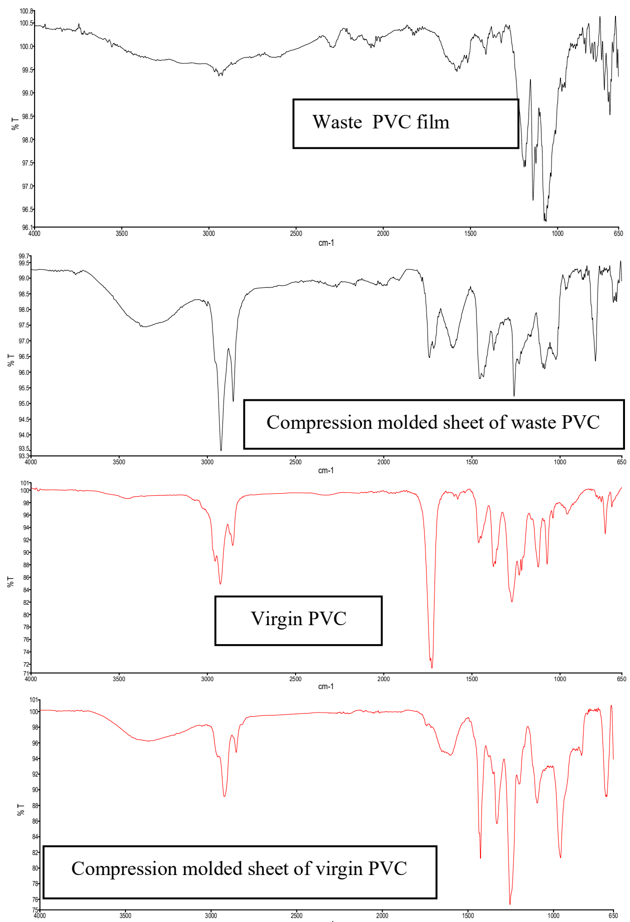


Figure 2 ATR-FTIR spectra of the waste PVC and the virgin PVC.

The characteristic C-Cl band of PVC was found around at 699-706 cm^{-1} region in both the waste PVC and the virgin PVC and the compression molded product of them. Other characteristic bands of PVC for C-C, $-CH_2$ and C-H bonds were found around the 1065-1095 cm^{-1}, 1412-1461 cm^{-1} and 1123 -2944 cm^{-1} regions, respectively. The spectra of PVC were almost the same as those reported in the literature [13-14]. Other bands found in all spectra of PVC were due to the presence of additives. It is also clear from the spectral analysis that the main chemical structure of the waste PVC and the virgin PVC did not change during the compression molding process.

Table 1 ATR FTIR peak assignments of waste PVC and virgin PVC.

Characteristic bonds of ATR-FTIR Peak Assignments	Wave number (cm^{-1}) of waste PVC	Wave number (cm^{-1}) of virgin PVC	Wave number (cm^{-1}) of compression molded waste PVC	Wave number (cm^{-1}) of compression molded virgin PVC
-CH	2,943.3	2,926.83	2,922.84	2,923.98
-CH	2,853.11	2,857.09	2,853.57	2,853.42
C=O	1,578.6	1,726.45	1,739.91	1,601.53
$-CH_2$	1,412.6	1,460.83	1,453.04	1,426.11
-CH	1,328.37	1,377.33	1,375.37	1,329.92
-CH	1,253.21	1,272.65	1,260.13	1,253.80
-CH	1,140.07	1,123.80	1,231.2	1,140.07
C–C	1,065.50	1,072.76	1,086.96	1,094.09
$-CH_2$	960.56	965.29	970.54	958.23
C-Cl	699.45	705.93	696.80	688.00

3.3 Tensile Properties of Waste PVC and Virgin PVC

The tensile strength and elongation at break (%) of the waste PVC film, the compression molded sheet of waste PVC, and the compression molded sheet of virgin PVC are presented in Figures 3 and 4 respectively. It can be seen from Figure 3 that the tensile strengths of the waste PVC film and the compression molded sheet of waste PVC were almost identical, but the tensile strength of the virgin PVC was higher than that of the waste PVC. This is due to the presence of plasticizer in virgin PVC.

The low level of plasticizer in PVC increases the tensile strength and elongation at break but with an increased plasticization level of the PVC beyond the plasticization threshold. Thus, the PVC becomes more flexible, with higher elongation at break and a lower tensile strength [15-16]. From Figure 4, it can be seen that the elongation at break (%) of the compression molded sheet of waste PVC decreased compared to the film of waste PVC. Thus, it can be said that reprocessing waste PVC reduces its ductility but does not affect its tensile strength. Mechanical recycling often decreases the tensile strength and elongation at break of recycled plastics [17]. The presence of plasticizer in virgin PVC increased its elongation at break (%) compared to the waste PVC film and the compression molded sheet of waste PVC.

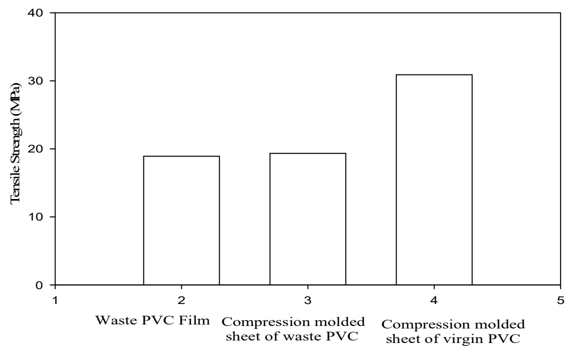


Figure 3 Tensile strength of the waste PVC and the virgin PVC.

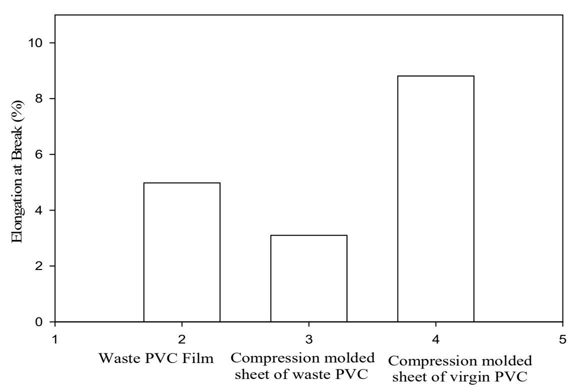


Figure 4 Elongation at break (%) of the waste PVC and the virgin PVC.

3.4 Thermal Properties of Waste PVC and Virgin PVC

The thermal properties of the waste PVC film, the compression molded sheet of waste PVC, and the compression molded sheet of virgin PVC were investigated by thermogravimetric analyses (TGA). The TGA curves are presented in Figures 5, 6, and 7, respectively. It is clear from these figures that the thermal stability of the compression molded sheet of waste PVC was slightly higher than that of the waste PVC film and the compression molded sheet of virgin PVC. Thus, applying compression molding increased the thermal stability of the waste PVC recyclates. The thermal decomposition temperature at onset (T_o), temperature at 60% weight loss (T_{60}), temperature at maximum weight loss (T_{max}), and temperature of residual mass of the waste PVC film, the compression molded sheet of waste PVC, and the compression molded sheet of virgin PVC are presented in Table 2. The degradation stage of PVC in the temperature ranges from 216 to 440 ºC is assigned to the progressive dehydrochlorination of the PVC and to the formation of a conjugated polyene structure [18]. Thermal cracking of the carbonaceous conjugated polyene sequences and the formation of residual chars occurs in a higher temperature range in the degradation stage of PVC [18].

Table 2 TGA data analyses of waste PVC and virgin PVC.

Sample name	T_o ºC and mass change (%) (approx.)	T_{60} ºC and mass change (%) (approx.)	T_{max} ºC and mass change (%) (approx.)	Residue (%) at ºC (approx.)
Waste PVC film	153.71 ºC and 0.22%	437.93 ºC and 59.28%	742.83 ºC and 98.78%	1.03% at 832.62 ºC
Compression molded sheet of waste PVC	216.46 ºC and 1.56%	432.20 ºC and 57.71%	764.29 ºC and 97.13%	2.27% at 844.01 ºC
Compression molded sheet of virgin PVC	233.53 ºC and 0.11%	430.14 ºC and 60.81%	726.16 ºC and 99.85%	0.02% at 830.54 ºC

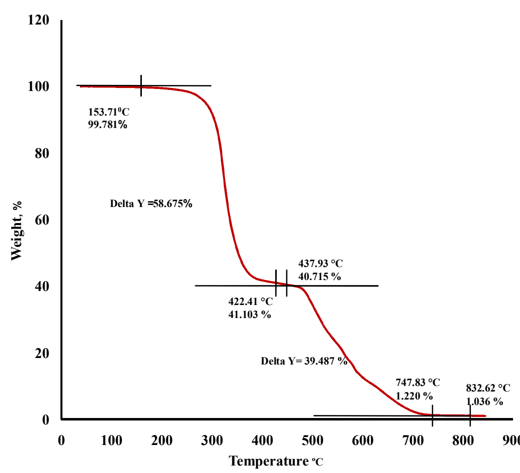


Figure 5 TGA of the waste PVC film.

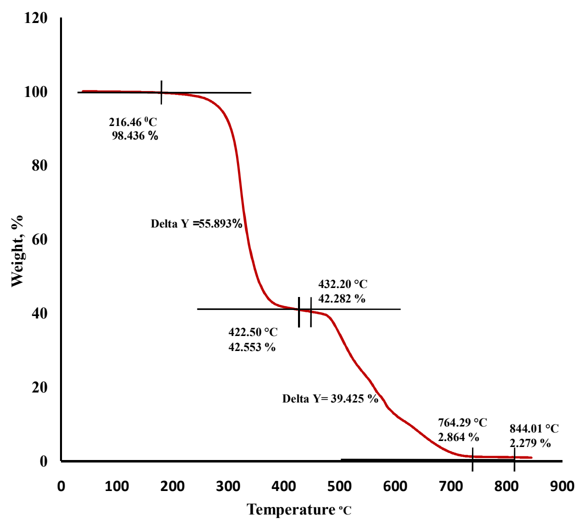


Figure 6 TGA of the compression molded sheet of waste PVC.

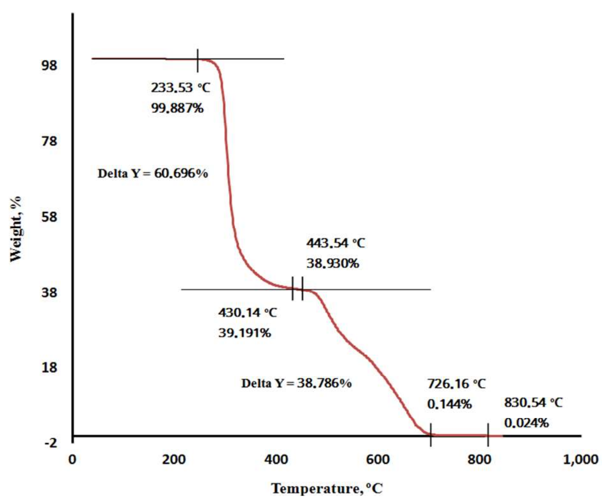


Figure 7 TGA of the compression molded sheet of virgin PVC.

3.5 Specific Gravity and Water Absorption of Waste PVC and Virgin PVC

The specific gravities of the compression molded sheet of waste PVC and the compression molded sheet of virgin PVC were measured per ASTM D 792-13. The results were 1.39 and 1.27, respectively. The difference in the specific gravity of the waste PVC and the virgin PVC was due to the presence of different types and amounts of additives. The presence of plasticizer in virgin PVC may reduce the specific gravity of virgin PVC compared to that of rigid waste PVC. The water absorption of the compression molded sheet of waste PVC and the compression molded sheet of virgin PVC was measured per ASTM D 590-98. The values were 0.87% and 0.99%, respectively. Pure PVC polymer is non-hygroscopic, and the water absorption results also showed evidence for a non-hygroscopic nature of the compression molded sheet of waste PVC and the compression molded sheet of virgin PVC.

4 Conclusion

Waste rigid poly(vinyl chloride) fill material was successfully utilized to prepare compression molded product. ATR-FTIR analysis revealed that the chemical structure of the waste PVC did not degrade during recycling to make the compression molded product. The tensile strength of the compression molded product of waste PVC did not decrease compared to the waste PVC film and a higher thermal stability was also achieved by the compression molded product of waste PVC compared to that of the waste PVC film and the compression molded product of virgin PVC. Thus, re-melting and re-molding of waste PVC into different new industrial products such as pipes, profiles, furniture, etc. can be useful to replace virgin PVC. It can be stated that cost-effective mechanical recycling of PVC waste can reduce its environmental impact and save virgin PVC resources.

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Conflict of Interest

The authors declare no conflict of interest related to this study.

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