Iranian Polymer Journal
https://doi.org/10.1007/s13726-024-01369-8

ORIGINAL RESEARCH

Influence of nucleating agent on the mechanical and thermal properties of neat isotactic polypropylene/reprocessed polypropylene blends

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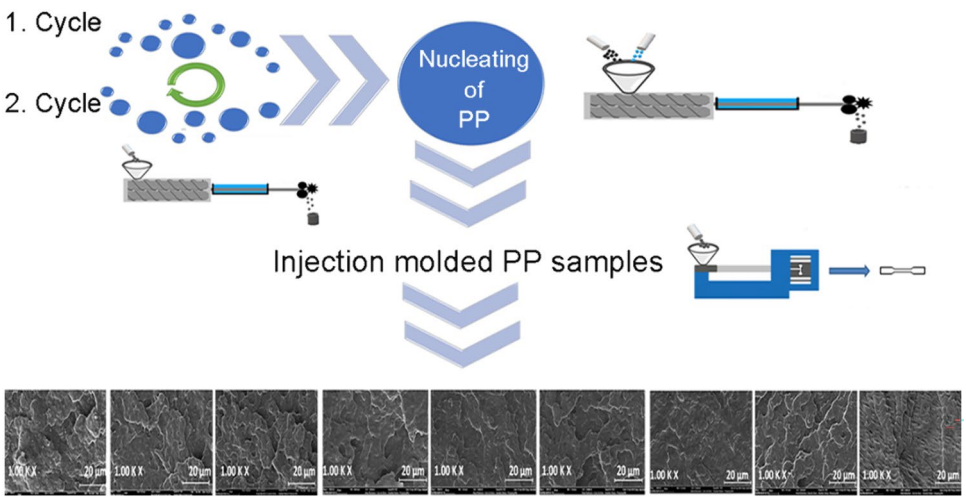
Received: 9 January 2024 / Accepted: 12 June 2024

Abstract

In recent years, recycling of polypropylene (PP) has gained significant attention for various industrial applications, namely post-industrial PP waste has great advantages in terms of circular economy. In this study, the effect of the amount of nucleating agent on the mechanical and thermal properties of polypropylene blends was investigated. Neat isotactic polypropylene and reprocessed polypropylene (iPP/rPP) were blended by means of a twin-screw extruder at 0/100, 50/50, 25/75 and 100/0% (by weight), respectively. The blends were processed by means of a twin-screw extruder then injection molded with the nucleating agent at different ratios (0, 1, 3 and 6% by weight). The properties of the samples were investigated by melt flow index (MFI) measurement, scanning electron microscope (SEM), tensile test, three point bending test and differential scanning calorimetry (DSC) analysis. The MFI values of the blends increased with the increasing amount of rPP. As a result of DSC analysis, the melting temperature of the blends increased by 1.4 °C with the presence of 6% (by weight) nucleating agent. The highest flexural modulus was obtained as 1863 MPa for the iPP/rPP0 blends with the addition of 6% (by weight) nucleating agent. The elastic modulus increased with the addition of nucleating agent from 1819 (iPP/rPP50NA0) to 2152 MPa (iPP/rPP50NA6). The iPP/rPP blend with a weight ratio of (50/50) exhibited mechanical and thermal properties similar to neat iPP with the presence of 3% (by weight) nucleating agent.

Graphical abstract



Keywords rPP · Nucleating agent · Injection molding · Recycling · Post-industrial waste

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Published online: 10 September 2024

Introduction

Polypropylene (PP) is one of the most widely used semi-crystalline commercial polymer [1, 2]. There are many advantages using PP for industrial products such as recycling [3, 4], economically [5] and easy processing compared to metals [6] and light weighting [7, 8]. PP provides the mechanical [9, 10], thermal [11] and optical [12] performance requirements of various applications such as automotive [13, 14], packaging [15, 16], white goods [17] and construction industry [18]. In recent years, the production quantity and consumption of PP raw materials have increased rapidly [19, 20]. The importance of recyclingof PP waste increased greatly due to reduced carbon dioxide (CO_2) footprint and sustainability of polymer industry [21, 22]. Especially, reprocessing of post-industrial PP waste has gained significant attention because of circular economy and the "European green deal" goals [23, 24] of automotive industry. Generally, post-industrial PP waste consists of runners, trimmings and defects of the PP products, such as short shot, warpage, shrinkage, etc. [25, 26]. Reprocessing cycles cause to thermal, thermo-oxidative and mechanical degradation of PP chains [27, 28]. The degradations are negatively affected, especially intensile strength, elastic modulus, flexural modulus, elongation at break, melt flow index, impact strength, color and molecular weight of PP [29, 30]. Strömberg et al. [31] reported that degradation mechanism potentially occurred in the PP during the reprocessing. The melt flow index of PP increases due to thermomechanical aging. Ladhari et al. [32] reported that mechanically recycled PP exhibited stiffer and more brittle behavior, reduced elongation at break and notched charpy impact strength compared to virgin PP. The physical and mechanical properties of PP were enhanced by various additives such as a filler, antioxidant, stabilizer, fiber and nucleating agent [33, 34]. Bernagozzi et al. [4] reported the effect of a commercial additive on the molecular weight of PP during multiple reprocessing cycles. The thermomechanical degradation of the pre-consumer and the post-consumer PP waste during a mechanical recycling process was evaluated by rheological and thermal tests. Commercial additives can effectively prevent the decrease of the molecular weight of PP. Wang et al. [36] reported that talc improved the mechanical properties of PP composites during reprocessing.

Nucleating agents are preferred especially to improve the physical and mechanical properties of semi-crystalline polymers [36, 37]. Generally, mineral-based additives are used as a nucleating agent for PP such as talc, calcite, clay, kaolin and phosphate ester salts [38, 39]. Nucleating agents provides better mechanical and physical properties due to the regularization of the polymer chains [40, 41]. In the presence of a nucleating agent, positive changes occur in the mechanical properties of the polymer by increasing the nucleation density and decreasing the spherulite dimensions [41, 42]. Zhang et al. [43] reported that the additions of lanthanum and cerium phenylphosphonates (only 0.05% by weight) increased the crystallization temperature of isotactic PP (iPP) and decreased the sizes of spherulites. Wei et al. [1] reported the effect of the nucleation agent on the crystallization and melting behavior of iPP compound under different crystallization processes. Xie et al. [44] investigated the effect of in situ synthesized nucleating agent on the mechanical properties and melting behavior of iPP. Pimelic acid and calcium stearate were added in situ during the extrusion of iPP to produce the nucleating agent. It was determined that the mechanical properties of iPP improved. Bao et al. [45] investigated the effect of multi-walled carbon nanotube (MWCNT) heterogeneous nucleating agent at different ratios on the crystallization behavior of PP. As a result of regularity of the crystal structure, the yield strength and Young's modulus improved. Zhao et al. [46] reported that the PP was nucleated by in situ method using zinc adipate as the nucleating agent. The nucleation efficiency, core number and toughness of iPP significantly increased. The efficiency of nucleating agent depends on the concentration, particle size, particle shape, physical state of the nucleating agent and process conditions [47, 48]. Luijsterburg et al. [16] reported the effect of processing parameters (cooling rate and pressure) on the structure behavior of neat and recycled iPP with and without a nucleating agent.

There are various studies in the literature on improving the thermal [1, 46] and mechanical properties of rPP and PP [16, 44]. However, there seems to be limited number of studies on the effect of the nucleating agent and rPP ratio on the properties of iPP/rPP blends in preceding literature. We aimed to improve the deterioration in the mechanical and thermal properties of rPP/PP blends caused by the reprocessing of post-industrial PP waste with the additon of a nucleating agent. In this study, the effects of the amount of nucleating agent on the mechanical and thermal properties of neat isotactic PP/reprocessed PP (iPP/rPP) blends were investigated. Neat iPP was reprocessed by using a twin-screw extruder to simulate recycling of post-industrial iPP waste. Reprocessed and neat iPP (iPP/rPP) were blended (0/100, 50/50, 25/75 and 100/0% (by weight)) without and with a nucleating agent (0, 1, 3 and 6% by weight) and then injection molded. The properties of the samples were investigated by melt flow index (MFI) measurement, scanning electron microscopy

(SEM), tensile test, three-point ending test and differential scanning calorimetry (DSC) analysis.

Experimental

Materials

iPP with the commercial name Petoplen MH-418 was obtained from PETKIM (Izmir, Turkey). iPP has a density value of 0.905 g/cm^3 according to the ASTM D1505 standard, heat deflection temperature value 110 °C at 0.45 MPa according to the ASTM D648 standard and Izod impact strength values of 22 J/m at 23 °C according to the ASTM D256 standard. The nucleating agent (Akkat Clarifier/Nucleator PP/F109311) was purchased from Aksoy Plastic Inc. (Istanbul, Turkey), is a masterbatch containing 10% (by weight) nucleating agent (NA) in the PP matrix.

Preparation of blends

This study was carried out under laboratory condition to model heat loading and mechanical stresses of neat iPP, which was exposed to reprocessing stage. Mechanical stresses are caused by mechanical degradation during grinding and processing [31]. Firstly, neat iPP was processed twice by using a co-rotating twin-screw extruder to obtain recycled PP. The extrusion temperature profile was 240 °C, 230 °C, 230 °C, 210 °C, 200 °C, 190 °C and 40 °C from the die to the feed zone. Then, neat iPP, rPP and their blends were extruded without and with a nucleating agent (0, 1, 3 and 6% by weight) after drying for 4 h at 100 °C. The formulation of iPP/rPP blends are given in Table 1. The prepared iPP/rPP granules were molded using Engel Spex 80 model injection molding machine after drying for 4 h at 100 °C. The injection temperature profile was 210 °C, 200 °C, 190 °C, 180 °C and 40 °C from the nozzle to the feed zone. The injection pressure was 50 bars and injection speed was 65 mm/s. The preparation process of the sample is given in Fig. 1.

Table 1 The formulation of the iPP/rPP blends

Sample	iPP % (by weight)	rPP % (by weight)	Nucleating agent % (by weight)
iPP/rPP0NA0	100	0	0
iPP/rPP0NA1	100	0	1
iPP/rPP0NA3	100	0	3
iPP/rPP0NA6	100	0	6
iPP/rPP50NA0	50	50	0
iPP/rPP50NA1	50	50	1
iPP/rPP50NA3	50	50	3
iPP/rPP50NA6	50	50	6
iPP/rPP75NA0	25	75	0
iPP/rPP75NA1	25	75	1
iPP/rPP75NA3	25	75	3
iPP/rPP75NA6	25	75	6
iPP/rPP100NA0	0	100	0
iPP/rPP100NA1	0	100	1
iPP/rPP100NA3	0	100	3
iPP/rPP100NA6	0	100	6

Characterization

Melt flow index analysis was performed using a Lloyd MFI 10-AX1 device according to the ASTM D1238 standard. MFI values of the samples were measured under the 230 °C and 2160 g load conditions.

The morphological behavior of the blends was investigated using scanning electron microscopy. Zeiss Supra 40 VP branded SEM device equipped with energy-dispersive X-ray analysis (EDX) was used in the analysis. SEM analysis was performed at 10.00 kV from the fracture surface of the injection-molded blends after tensile tests. The surfaces of all blends were coated with gold–palladium (Au–Pd) before SEM analysis.

The flexural tests were carried out using the three-point bending test method according to the ASTM E2769 standards. Flexural tests were performed at room temperature with an Instron 4411 H4203 device. The average value of three measurements for each sample was calculated.

Tensile tests were performed at room temperature according to the ASTM D638 standard. Tensile test specimens were kept in the laboratory environment for 48 h. Then, tensile tests were performed at room temperature with an Instron 4411 device. The average value of five measurements for each sample was calculated.

Differential scanning calorimetry analyses were performed by means of a Shimadzu 60 Plus DSC device

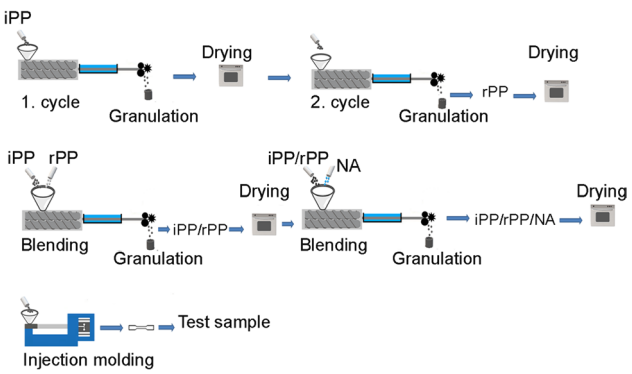

Fig. 1 Preparation process of iPP/rPP blends

according to the ASTM D3418 standard. The DSC analysis was performed at a constant heating and cooling rate of 10 °C/min under nitrogen atmosphere with heating temperature range of 25–200 °C and cooling temperature range of 200–25 °C.

Results and discussion

Results of melt flow index measurement

The effects of the amount of nucleating agent on the melt flow behavior of PP blends were investigated. MFI valuesof the neat iPP, rPP and their blends are given in Fig. 2 and Table 2. It was observed that MFI values of the iPP/rPP blends do not change significantly with the increasing amount of nucleating agent as depicted in Fig. 2a. There was an average difference of 0.7% for MFI values of the blends with nucleating agent compared to neat iPP. On the other hand, the increase in the amount of rPP in the blends without nucleating agent increased the MFI value of the blends as shown in Fig. 2b. The MFI values of iPP/rPP0NA0, iPP/rPP50NA0, iPP/rPP75NA0 and iPP/rPP100NA0 are 5.11, 12.35, 13.94 and 23.44 g/10 min, respectively. The iPP/rPP100 blend with the addition of 1% (by weight) nucleating agent exhibited the highest MFI values (23.46 g/10 min). iPP/rPP0 with the addition of 6% (by weight) nucleating agent exhibited the lowest MFI values (5.03 g/10 min). It is seen that the amount of rPP is effective on the fluidity of iPP/rPP blends than the amount of nucleating agent in the blends. The MFI value of rPP increased by about five times compared to neat iPP. This is an indication of the degradation of the PP during the reprocessing cycles caused by the polymer chain scission [23]. Aurrekoetxea et al. [29] reported that recycling had a lowering effect on the melt viscosity of PP due to the decrease in molecular weight. Wang et al. [36] reported thermo-mechanical degradation of PP/talc composites during multiple extrusions. The neat PP exhibited an increase of melt flow index value with the number of cycles caused by a decrease of molecular weight due to chain scissions of PP. The decrease of the molecular weight of reprocessed PP was prevented in the presence of the additive. The flow properties and processability of reprocessed PP were enhanced with the additive [4]. This variation in MFI value is part of the challenge of using reprocessed PP for injection molding. The MFI value is used to control reprocessed PP and neat PP blend properties. These are not affected by mechanical properties [6].

Table 2 MFI, hardness and flexural modulus values of neat iPP, rPP and their blends

Sample	MFI (g/10 min)	Hardness (Shore D)	Flexural modulus (MPa)
iPP/rPP0NA0	5.11	68.10	1770
iPP/rPP0NA1	5.09	68.20	1810
iPP/rPP0NA3	5.05	68.10	1829
iPP/rPP0NA6	5.03	68.00	1863
iPP/rPP50NA0	12.35	69.50	1610
iPP/rPP50NA1	12.35	69.20	1560
iPP/rPP50NA3	12.29	69.20	1630
iPP/rPP50NA6	12.27	69.20	1730
iPP/rPP75NA0	13.94	69.60	1383
iPP/rPP75NA1	13.96	69.50	1477
iPP/rPP75NA3	13.88	69.60	1515
iPP/rPP75NA6	13.86	69.70	1650
iPP/rPP100NA0	23.44	67.70	1238
iPP/rPP100NA1	23.46	69.60	1410
iPP/rPP100NA3	23.35	69.70	1450
iPP/rPP100NA6	23.28	69.60	1382

Results of the flexural test

The effect of the amount of nucleating agent on the flexural properties of PP blends was investigated. The results of flexural test of the neat iPP, rPP and their blends are given in Fig. 3 and Table 2. It was observed that the amount of

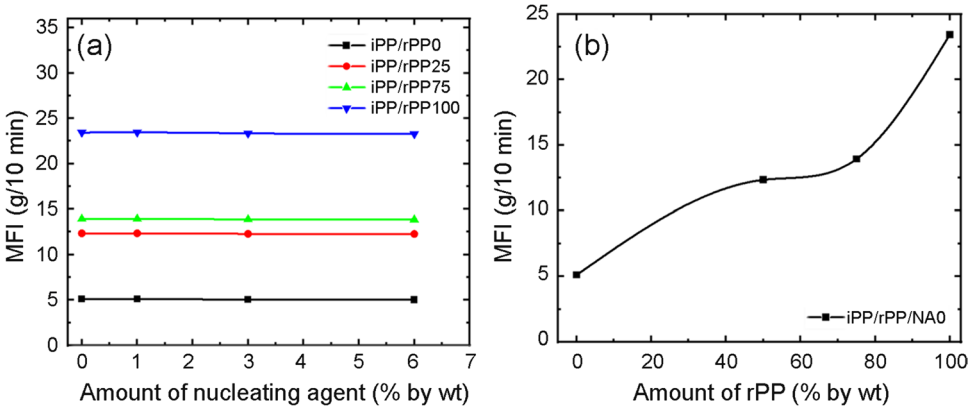

Fig. 2 **a** Effect of the amount of nucleating agent on the MFI value of iPP/rPP blends and **b** the MFI values of iPP/rPP blends without the nucleating agent

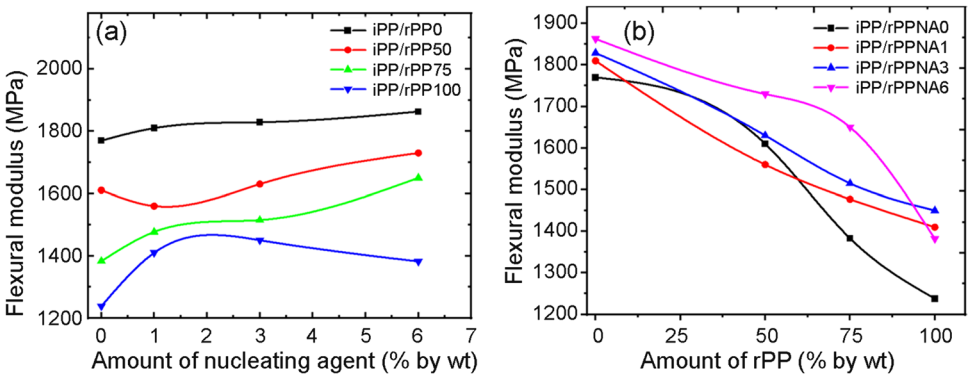

Fig. 3 **a** Effect of the amount of the nucleating agent on the flexural modulus of the blends and **b** effect of the amount of rPP on the flexural modulus of the blends

rPP and nucleating agent affected the flexural modulus of the iPP/rPP blends (Fig. 3b). Increasing amount of rPP decreased the flexural modulus compared to neat iPP. The flexural modulus of iPP/rPP0NA0, iPP/rPP50NA0, iPP/rPP75NA0 and iPP/rPP100NA0 was 1770, 1610, 1383 and 1238 MPa, respectively. The flexural modulus of rPP is approximately 32% lower than that of neat iPP. The mechanical properties of reprocessed post-industrial PP waste blends were decreased after each reprocessing cycle. It was found that the addition of the nucleating agent could effectively increase the flexural modulus of iPP/rPP0, iPP/rPP50, iPP/rPP75 and iPP/rPP100 blends. The iPP/rPP0 blends with the addition of 6% (by weight) nucleating agent exhibited the highest flexural modulus (1863 MPa). The increase of flexural modulus of iPP/rPP100 blends can cause increase in boundary strength between the spherulites which is provided with SEM micrographs.

Wang et al. [36] reported that a small quantity of nucleating agent could significantly increase the flexural modulus of the PP. It was found that the addition of the nucleating agent improved the flexural modulus of iPP. Thus, using a nucleating agent causes saving cost, gaining enhanced mechanical properties for reprocessing or recycling of PP.

Results of tensile test

The effect of the amount of nucleating agent on the tensile properties of PP blends was investigated. The breaking strength, elongation at yield, yield strength, elongation at break and elastic modulus of the neat iPP, rPP and their blends are given in Fig. 4 and Table 3, respectively. It was observed that the amount of rPP and nucleating agent affected the tensile properties of the iPP/rPP blends. The increasing of the amount of nucleating agent increased the elastic modulus compared to neat iPP in Fig. 4a. The increase in the amount of rPP decreased the elastic modulus compared to neat iPP as shown in Fig. 4b. The elastic modulus of iPP/rPP0NA0, iPP/rPP50NA0, iPP/rPP75NA0 and iPP/rPP100NA0 was 1959 1819 1662 and 1632 MPa, respectively. The mechanical properties are adversely affected by the presence of recycled polymer [49, 50]. The decrease of mechanical properties is due to the shortening of the chain length caused by the reprocessing. Jamnongkan et al. [19] reported that the modulus and tensile strength of PP/recycled PP (rPP) decreased with the increase in rPP concentrations. The elastic modulus increased with the addition of nucleating agent in both iPP/rPP blends with the weight ratios of (50/50) and (25/75). Because of the crystalline morphology change of iPP/rPP blends, the values of the elastic modulus increased with the addition of nucleating agent from 1662 (iPP/rPP75NA0) to 2065 MPa

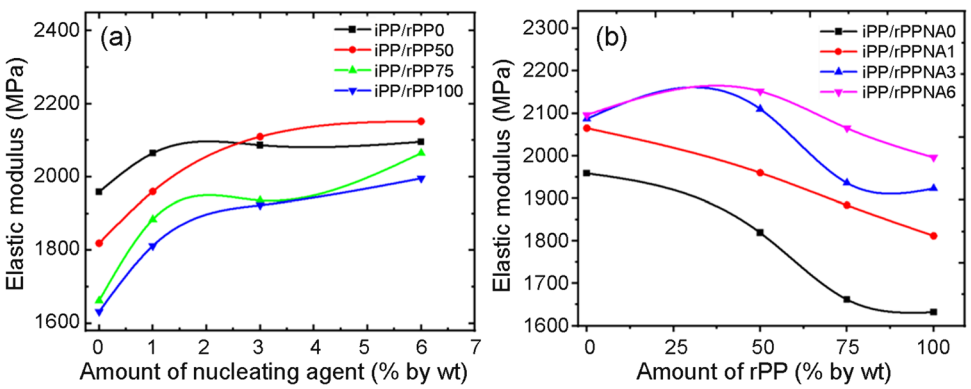

Fig. 4 **a** Effect of the amount of nucleating agent on the elastic modulus and **b** effect of the amount of rPP on the elastic modulus of the blends

Table 3 The tensile test results of neat iPP, rPP and their blends

Sample	Elastic modulus (MPa)	Elongation at yield (%)	Yield strength (MPa)	Elongation at break (%)	Breaking strength (MPa)
iPP/rPP0NA0	1959 ± 39	6.6 ± 0.1	36 ± 0.1	30.0 ± 5.5	15 ± 2.2
iPP/rPP0NA1	2065 ± 19	6.0 ± 0.1	38 ± 0.2	18.0 ± 3.1	26 ± 3.4
iPP/rPP0NA3	2087 ± 13	5.6 ± 0.1	39 ± 0.1	17.8 ± 1.4	26 ± 1.5
iPP/rPP0NA6	2096 ± 14	5.5 ± 0.1	39 ± 0.2	14.3 ± 4.6	29 ± 3.0
iPP/rPP50NA0	1819 ± 15	7.5 ± 0.1	36 ± 0.2	37.4 ± 9.4	16 ± 3.3
iPP/rPP50NA1	1960 ± 30	6.9 ± 0.1	37 ± 0.2	18.7 ± 2.9	25 ± 4.0
iPP/rPP50NA3	2110 ± 29	6.0 ± 0.1	38 ± 0.2	17.8 ± 3.1	26 ± 3.4
iPP/rPP50NA6	2152 ± 15	5.6 ± 0.1	39 ± 0.2	18.0 ± 1.4	26 ± 1.5
iPP/rPP75NA0	1662 ± 47	8.3 ± 0.2	35 ± 0.5	49.0 ± 7.9	11 ± 2.3
iPP/rPP75NA1	1884 ± 20	7.3 ± 0.1	37 ± 0.3	21.7 ± 4.3	18 ± 7.7
iPP/rPP75NA3	1936 ± 55	6.9 ± 0.1	37 ± 0.1	21.5 ± 11.3	22 ± 5.1
iPP/rPP75NA6	2065 ± 48	6.1 ± 0.1	38 ± 0.3	13.5 ± 1.2	29 ± 2.8
iPP/rPP100NA0	1632 ± 19	8.8 ± 0.1	35 ± 0.4	51.0 ± 19.8	10 ± 4.3
iPP/rPP100NA1	1812 ± 33	7.8 ± 0.1	36 ± 0.3	25.5 ± 13.3	18 ± 6.3
iPP/rPP100NA3	1923 ± 28	7.1 ± 0.1	37 ± 0.4	15.6 ± 4.4	28 ± 3.4
iPP/rPP100NA6	1996 ± 24	6.7 ± 0.1	38 ± 0.4	14.4 ± 4.8	29 ± 3.3

(iPP/rPP75NA6). iPP/rPP50NA6 with the addition of 6% (by weight) nucleating agent exhibited the highest elastic modulus (2152MPa). Similar results were also observed for flexural modulus (Fig. 3).

The increase in the amount of nucleating agent increased the yield and breaking strength of the iPP/rPP blends. The breaking strengths of iPP/rPP0NA0, iPP/rPP50NA0, iPP/rPP75NA0 and iPP/rPP100NA0 were 15, 16, 11 and 10 MPa, respectively. The breaking strength increased with the addition of the nucleating agent from 10 (iPP/rPP100NA0) to 29 MPa (iPP/rPP100NA6) as given in Fig. 5. The difference in improvement of yield and breaking strength of iPP/rPP blends result from crystallinity.

The elongation at break of the iPP/rPP blends was improved with the increasing amount of rPP in the blends as given in Fig. 5. The elongation at break of iPP/rPP0NA0, iPP/rPP50NA0, iPP/rPP75NA0 and iPP/rPP100NA0 was 30.0, 37.4, 49.0 and 51.0%, respectively. Increasing the amount of nucleating agent decreased the elongation at break and elongation at yield of the iPP/rPP blends. The iPP/rPP75 with the addition of 6% (by weight) nucleating agent exhibited the lowest value of elongation at break (13.5%). The addition of a nucleating agent modified the crystallization behavior of rPP, enhancing its mechanical and surface properties. Tensile test results were also supported by DSC analysis and SEM micrographs.

Results of differential scanning calorimetry analysis

The effect of the amount of nucleating agent on the thermal behavior of PP blends was investigated. The melting temperature (T_m) of iPP, rPP and their blends are given in Fig. 6a and Table 4. It was observed that the melting temperature of iPP increased as the amount of nucleating agent increased. On the other hand, the amount of rPP caused a decrease in the onset melting temperature, from 160.40 (iPP/rPP0) to 155.04 °C (iPP/rPP100). Ajorloo et al. [23] reported that the melting temperature of recycled PP was lower than that of virgin PP because of the lower molecular weight of the polymeric chains. It was observed that the amount of rPP and nucleating agent affected the crystallization temperature of the iPP/rPP blends.

The crystallization temperature (T_c) of iPP, rPP and their blends are given in Fig. 6b and Table 4. The increase in the amount of rPP decreased the crystallization temperature from 121.73 to 116.56 °C. The crystallization temperature of rPP is as low as 5.2 °C compared to neat iPP. Xie et al. [44] reported that the crystallization temperature increased by 4–5 °C in the presence of the nucleating agent in iPP compared to neat iPP. Craig et al. [49] reported that the shorter polymer chains increased the crystallinity of PP. The addition of nucleating agent increased the crystallization temperature. The increase in crystallization temperature causes a decrease in injection molding cycling. Zhu et al. [40] reported that the crystallization temperature of rPP changed in the presence of the nucleating agent. The crystallization temperature of iPP/rPP100 (116.56 °C) increases by about 16% in the presence of 6% (by weight) nucleating agent. (121.73 °C). As a result, the cycle time in the injection molding of PP efficiency increased, thanks to the nucleating agent [51, 52]. The injection molding processing cycle of iPP/rPP blend was significantly shortened owing

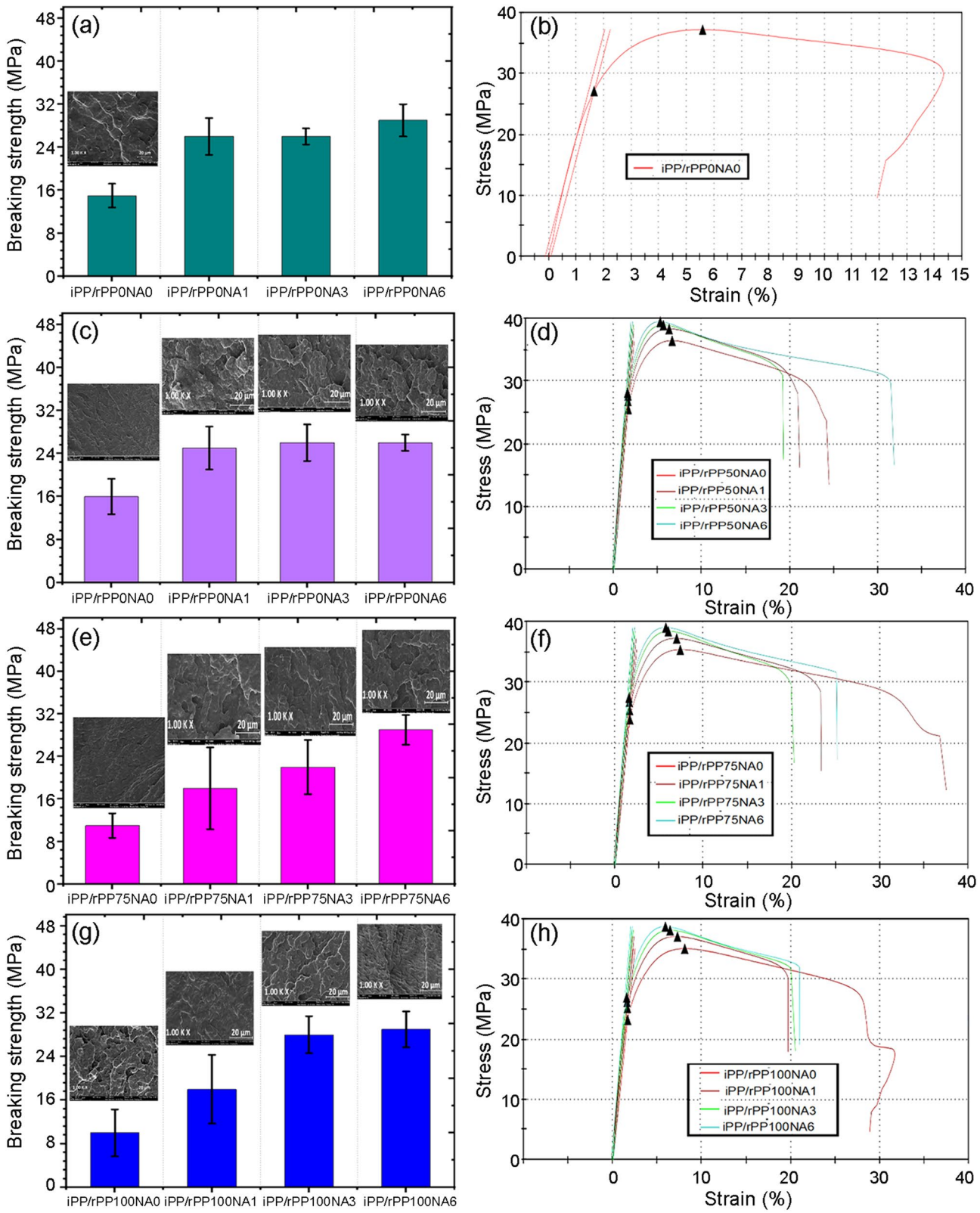

Fig. 5 **a** The breking strength graph of the iPP/rPP0 blends, **b** the stress and strain graph of the iPP/rPP0 blends, **c** the breking strength of the iPP/rPP50 blends, **d** the stress and strain graph of the iPP/rPP50 blends, **e** the breking strength of the iPP/rPP75 blends, **f** the stress and strain graph of the iPP/rPP75 blends, **g** the breking strength of the iPP/rPP100 blends and **h** the stress and strain graph of the iPP/rPP100 blends

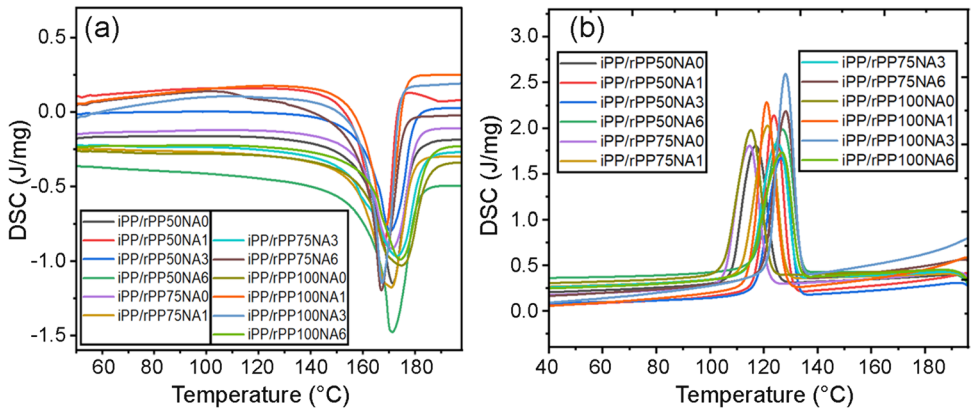

Fig. 6 DSC thermograms at **a** melting stages and **b** cooling stages of the iPP/rPP blends

Table 4 The melting and crystallization temperature of neat iPP, rPP and their blends

Sample	T_m^{Onset} (°C)	T_m^{Peak} (°C)	T_m^{Endset} (°C)	T_c^{Peak} (°C)
iPP/rPP0NA0	160.40	166.10	174.71	121.73
iPP/rPP0NA1	158.32	166.18	171.21	123.44
iPP/rPP0NA3	158.45	166.97	171.63	128.37
iPP/rPP0NA6	162.91	167.48	173.13	131.11
iPP/rPP50NA0	156.89	164.49	175.97	119.52
iPP/rPP50NA1	157.33	167.81	174.60	120.01
iPP/rPP50NA3	155.35	166.79	172.92	127.11
iPP/rPP50NA6	159.45	165.97	173.07	129.00
iPP/rPP75NA0	156.96	166.54	174.81	117.31
iPP/rPP75NA1	153.70	165.96	171.95	120.11
iPP/rPP75NA3	153.69	166.17	174.26	125.69
iPP/rPP75NA6	152.25	167.61	174.96	128.61
iPP/rPP100NA0	155.04	167.10	173.26	116.56
iPP/rPP100NA1	155.92	167.20	172.84	118.79
iPP/rPP100NA3	155.30	167.55	172.40	126.77
iPP/rPP100NA6	154.91	167.31	172.76	128.64

to the addition of the nucleating agent [38, 53]. Phulkerd et al. [48] reported that the addition of 0.5% (by weight) sodium 2,2′-methylene-bis-(4,6-di-*tert*-butylphenyl) phosphate and 1,3:2,4-bis(3,4-dimethylbenzylidene) sorbitol as a nucleating agent enhanced the crystallization temperature of iPP. The brittleness of rPP decreased on increasing the amount of the nucleating agent due to the increase in the rPP crystallization rate. As a result, the thermal and mechanical properties of iPP/rPP blends were similar to neat iPP with the addition of the nucleating agent.

Results of SEM analysis

The effect of the amount of nucleating agent on the morphological behavior of PP blends was investigated by SEM analysis. The SEM micrographs of the tensile fractured surface of iPP/rPP0NA0, iPP/rPP50NA0 and iPP/rPP75NA0 and iPP/rPP100NA0 at × 1000 magnification are given in Fig. 7. It was observed that the plastic deformation behavior of the iPP/rPP0NA0 fracture surface was clearly different from that of iPP/rPP100NA0. The reprocessing or recycling of PP leads to a clear reduction in the ductile properties [54].

The SEM micrographs of the tensile fractured surface of iPP/rPP50NA0, iPP/rPP50NA1, iPP/rPP50NA6, iPP/rPP75NA0, iPP/rPP75NA1, iPP/rPP75NA6, iPP/rPP100NA0, iPP/rPP100NA1 and iPP/rPP100NA6 at × 1000 magnification are given in Fig. 8. It was observed that the ductile behaviors of the blends' fracture surface were clearly different without and with the nucleating agent in the PP blends. On the other hand, increasing the amount of rPP without and with the nucleating agent affected the morphological behavior of the PP blends. The fracture surfaces of

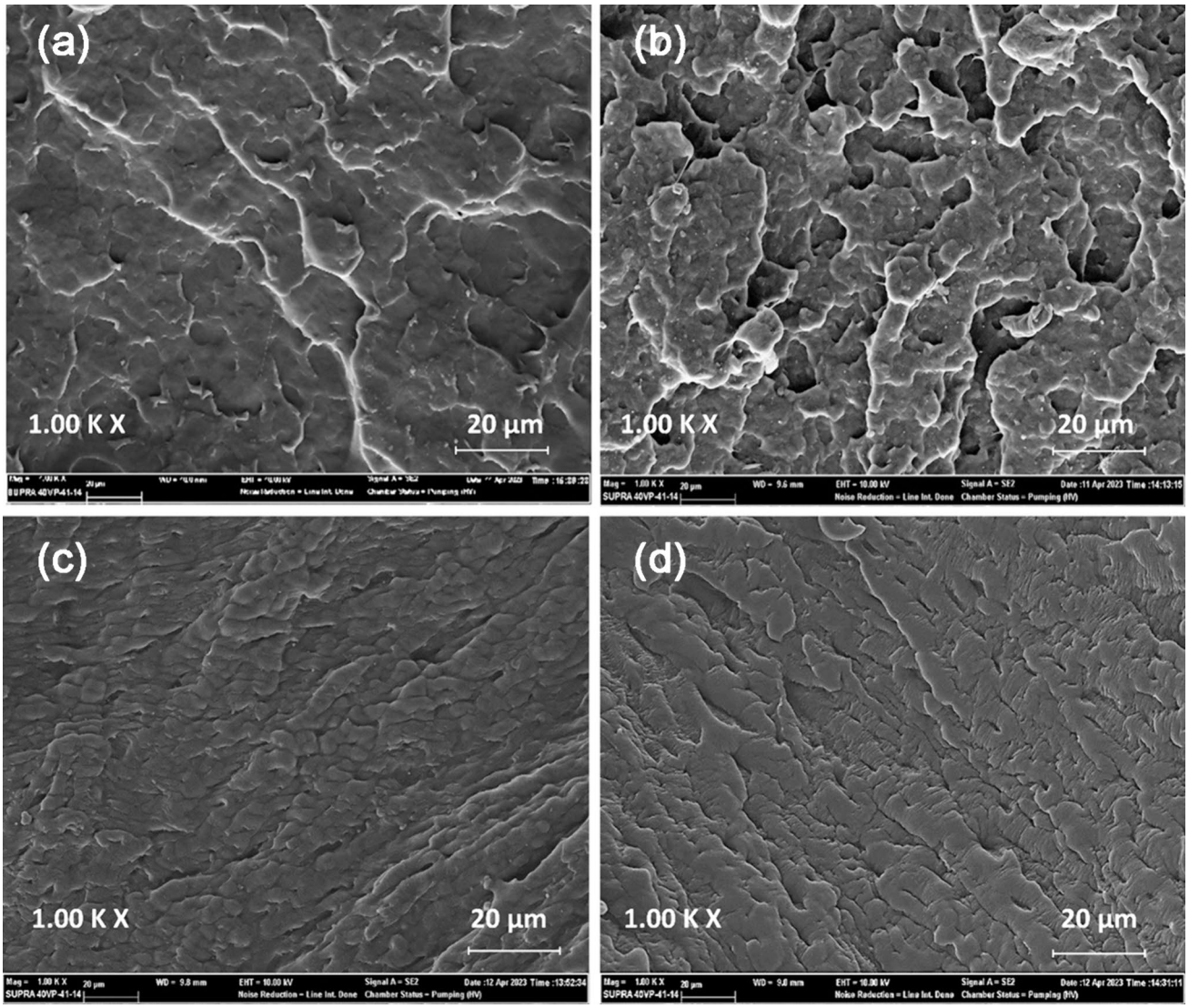

Fig. 7 The SEM micrographs of the fracture surface of **a** iPP/rPP0NA0, **b** iPP/rPP100NA0, **c** iPP/rPP50NA0 and **d** iPP/rPP75NA0 at × 1000 magnification

the PP blends without nucleating agent are much rougher than that of PP blends with nucleating agent. The SEM micrographs were compatible with the literature [55, 56]. Xu et al. [54] investigated the effects of molecular weight of isotactic polypropylene on the impact strength of nucleated isotactic polypropylene. The PP with high content of nucleating agent is less rough than those with low content of nucleating agent. The differences in the rough fracture surfaces of the blends exhibited an improvement in tensile strength of PP.

Conclusion

In this study, the effects of the nucleating agent on the mechanical and thermal properties of the iPP/rPP blends were investigated. We found that the rPP properties can be enhanced by the addition of a nucleating agent. The MFI values of the blends increased from 5.11 to 23.44 g/10 min with an increasing amount of rPP. The mechanical properties, such as elastic modulus, breaking strength, flexural modulus and yield strength, decreased with the increasing the amount of rPP. The mechanical properties of the blends decreased with the increasing amount of rPP, while it increased with the addition of the nucleating agent. The crystallization temperatures of the blends decreased from 160.40 to 155.04 °C with the increasing the amount of rPP. The crystallization temperature

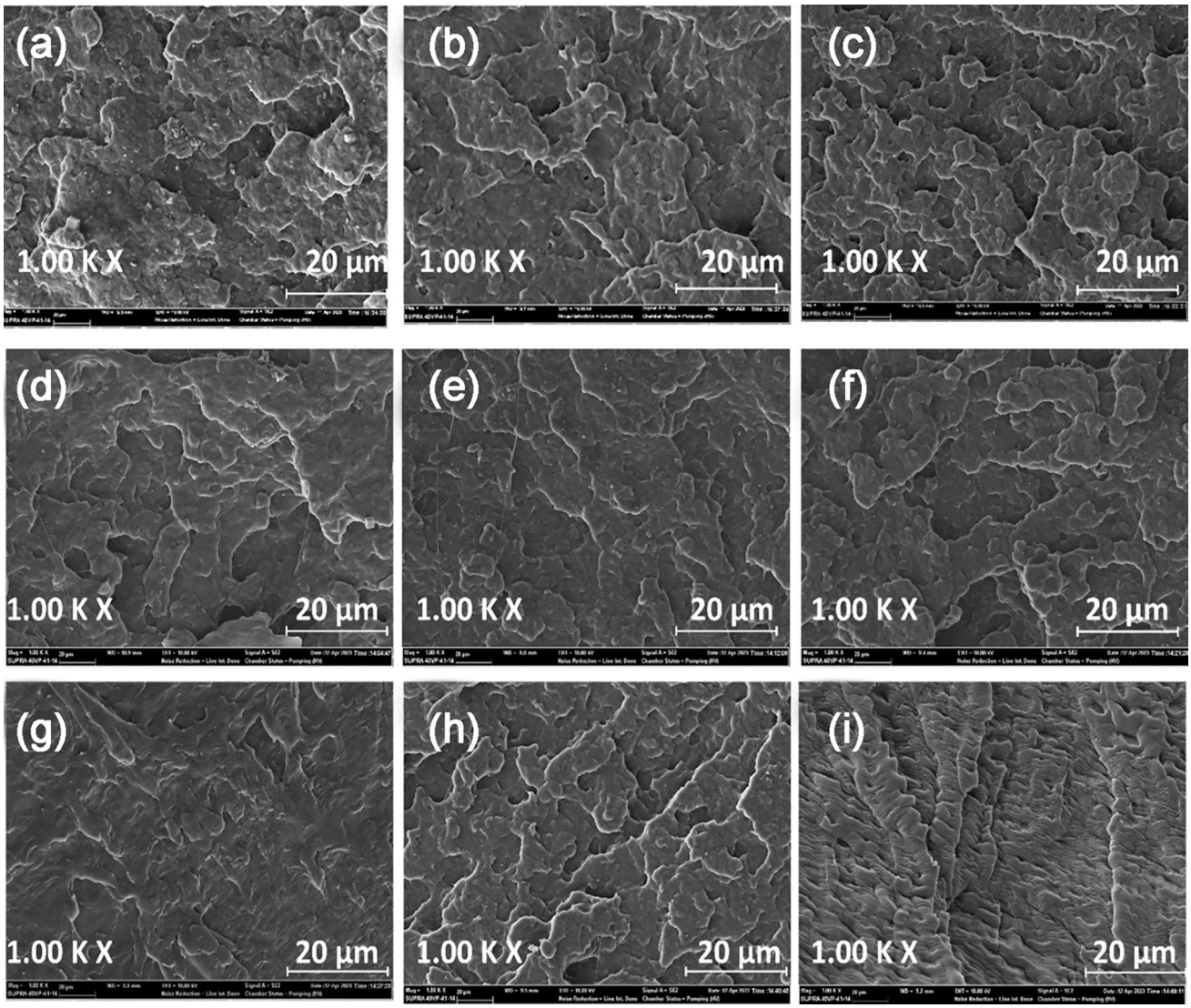

Fig. 8 The SEM micrographs of the tensile fractured surface of **a** iPP/rPP50NA1, **b** iPP/rPP50NA3, **c** iPP/rPP50NA6, **d** iPP/rPP75NA1, **e** iPP/rPP75NA3, **f** iPP/rPP75NA6, **g** iPP/rPP100NA1, **h** iPP/rPP100NA3 and **i** iPP/rPP100NA6 at × 1000 magnification

values of the blends increased by adding the nucleating agent. As a result, it has been seen that post-industrial PP waste can be an alternative to neat iPP within a nucleating agent for engineering application. In this study, the focus has been on improving the properties of PP waste in industrial waste, but it can be used in improving the properties of post-consumer PP waste and prevent the accumulation of this waste in the environment.

Acknowledgements The authors thank PETKIM, Inc.

Author contribution Mete Evren Berktas: Investigation, methodology and characterization; Aysun Ekinci: Characterization, conceptualization and writing; Mustafa Oksuz: Investigation, characterization, methodology and writing; Murat Ates: Characterization and writing; Ismail Aydin: Writing and reviewing.

Data availability Not applicable.

Declarations

Conflict of interest The authors declare no competing interests.

Ethical approval Not applicable.

Code availability Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

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