



Revolutionizing Impact Strength: Innovations in Compounding for Polypropylene Copolymers

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Abstract

The typical polypropylene impact copolymer (ICP) is composed of a substantial amount of ethylene-containing ethylene-propylene random copolymer (EPR) and isotactic polypropylene homopolymer. Its production involves consecutive polymerization in multiple reactors. Despite the advantages of ICPs over homopolymer polypropylene (HPP), certain applications necessitate specific ICP features, particularly the balance between impact strength and stiffness (*I/S*). However, technical limitations constrain the maximum EPR level and the highest isotacticity in the homopolymer continuous phase, critical for controlling the *I/S* balance. This research investigates two blend systems: the first involving the combination of ICP with HPP, and the second entailing the blending of various ICP grades. Three high-performance polypropylene (HPP) grades with distinct melt flow rates were utilized as a non-continuous phase, while grades of ICP with different ethylene-rubber phases and molecular weights served as the continuous phase. Incorporating 25% HPP into the continuous phase did not result in improved stiffness and impact strength in the final blend products. However, blending different ICPs demonstrated enhanced resilience. The findings highlight that a rubber mixture with evenly distributed particles and uniform size distribution significantly improves impact resistance. Specifically, one blend exhibited a remarkable 52% increase in impact resistance compared to the original ICP, while another blend showed a commendable 20% increase. In conclusion, this evaluation emphasizes the importance of a specific formulation, demonstrating that a well-distributed rubber composition and uniform particle size distribution significantly enhance impact resistance in specific blends, surpassing the performance of the original ICP.

Keywords: Impact strength/resistance 1; Impact Copolymer PP(ICP) 2; Blends 3

1. Introduction

Isotactic polypropylene (iPP) was introduced in the 1950s and has since gained popularity due to its improved strength and temperature endurance over other polyolefins [1]. The propylene polymerization

process was revolutionized by advancements in catalyst technology and manufacturing equipment. As a result, polypropylene (PP) has emerged as a leading choice owing to its flexibility, affordability, and superior performance compared to other polyolefins [2]. This polymer, which may be

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produced using many methods, has been widely used in numerous forms and sectors. Since the 1980s, ongoing progress in catalysts and improvements in quality have increased the production, consumption, and uses of polypropylene (PP), establishing it as the most extensively used thermoplastic worldwide [3]. PP, despite its strong mechanical qualities, has been extensively studied to address the limits in its low-temperature impact strength [3,4]. An enhancement that has been suggested is the combination of isotactic homopolymer (iPP) with ethylene-propylene random copolymer (EPR) that has high ethylene content. This combination is achieved by successive polymerization in different reactors, resulting in the formation of polypropylene impact copolymer (ICP) [3,5]. Polypropylene impact copolymers (ICP) are composed of a blend of ethylene-containing ethylene-propylene random copolymer (EPR) and isotactic polypropylene homopolymer. These materials offer advantages over high-performance polypropylene (HPP) in terms of impact resistance. However, there are technical constraints that impose limitations on the maximum EPR level and the degree of isotacticity in the homopolymer continuous phase. The maximum EPR level is restricted due to the need to maintain a balance between impact resistance and other mechanical properties. Higher levels of EPR can enhance impact resistance, but they may also lead to reduced tensile strength, stiffness, and heat resistance. Therefore, it is crucial to find an optimal EPR level that provides the desired impact resistance while preserving other important mechanical properties. Similarly, the isotacticity of the polypropylene homopolymer continuous phase

is another technical constraint. Isotacticity refers to the arrangement of the propylene monomer units in the polymer chain. A high degree of isotacticity is desired as it contributes to improved mechanical properties [5-7]. However, achieving high isotacticity becomes challenging as the EPR content increases. The presence of EPR disrupts the crystalline structure of the polypropylene, leading to reduced isotacticity and potentially compromising mechanical performance. These technical constraints highlight the need for innovative compounding approaches to optimize the properties of ICP. By blending ICP with HPP or varying the grades of ICP, researchers can explore methods to enhance impact resistance while mitigating the negative effects on other mechanical properties. The study aims to address these challenges and investigate the impact of different compounding approaches on the strength of ICP. By providing a more detailed explanation of these technical constraints, the introduction will offer readers a better understanding of the specific challenges and motivations underlying the research conducted in this study [8,9]. At present, the production of ICP mostly depends on either high-pressure processing (HPP) or isotactic polypropylene (iPP) as the continuous phase. However, there are limits in terms of the maximum EPR level and the greatest isotacticity that can be achieved from the homopolymer continuous phase. The dispersion or distribution of EPR particles in the HPP phase is achieved in the second reactor [10,11]. However, the ability to regulate the amount of ethylene, EPR content, and its distribution in the iPP phase is typically restricted in order to achieve optimal impact resistance at low temperatures. This is

because having excessively high ethylene content or EPR levels exceeding 45% wt% can result in inadequate dispersion of the non-continuous phase and potential problems in the reactor. Comprehending the specific technical constraints of each ICP technology lays the groundwork for suggesting novel enhancements to attain essential functionalities. Previous research focused on improving ICP by combining it with materials that have the desired properties, preferably from the same or other material groups [12-18]. The compatibility or miscibility of the blend is contingent upon parameters such as the structure of the polymer, the ratio at which it is blended, and the temperature at which the blending process takes place [19,20]. Phase separation during crystallization happens when an incompatible mixture is unable to retain a specified composition or phase ratios. Using a compatibilizer throughout the formulation may enhance the compatibility or miscibility between phases, hence improving the mechanical properties [21]. Nevertheless, increased concentrations of the non-continuous component within the identical group or incompatible mixtures often result in the separation of phases. There is a scarcity of research that especially focuses on ICP combinations. A study conducted by S. Paul and D. Kale [22], highlighted the significance of elastomer content in increasing impact properties and achieving a balanced morphology. This research stressed the relevance of enhancing features via the manipulation of elastomer content. Xuanbo Liu et al. [23] investigated blends obtained from the same ICP as the continuous phase and two different HDPEs, emphasizing the substantial influence of morphology and molecular weight on

characteristics. Peng et al. [13] demonstrated the relationship between the loading of rubber phase, blend morphology, and the final impact properties. Additionally, the loading of ICP had an influence on the thermal characteristics. In addition, the combination of ICP with another polyolefin has been shown to improve sheet extrusion qualities [24]. This work investigates a number of blends of ICP (Isotactic Polypropylene) and polyolefin, taking into account the importance of ICP and the limited amount of experimental data available on ICP-polyolefin blending. The inquiry incorporates supplementary HPP grades as a non-continuous phase with the objective of improving stiffness and/or impact resistance. Another series incorporates supplementary ICP grades as the non-continuous phase to enhance mechanical performance via synergy with the matrix. The purpose of analyzing and evaluating these samples is to determine the most effective combinations that promote improved dispersion of rubber inside the ICP matrix, leading to higher impact strength and resistance.

2. Materials and Methods

2.1 Materials

Three different ICP grades (48MK40 (A), 57MNK10 (B), and FPC75 (D) as well as three different polypropylene homopolymers (PP500P (E), PP518A (F), and PP519A (G) were employed in this study. These materials are listed in **Table 1**. All materials obtained from Saudi Basic Industries Corporation (SABIC), Saudi Arabia. In **Table 2**, the characteristics of the HPP and ICP grades materials are displayed in detail.

The basic molecular characteristics and EPR morphology are given in Table2. The results

show significant difference in either Mw or Mn of the different ICP grades. All ICP grades were characterized for the quantification and/or the presence of TBA i.e. tert-Butyl Alcohol using Headspace Gas Chromatography test. Amongst, the three ICP, only ICP (B) showed presence of TBA as an indication of visbreaking "chains scission". A slight difference in either C2 or EPR. Based on the above data, there is a clear variation in resulted intrinsic viscosity ratio between dispersed phase EPR and homopolymer matrix of the different grades, which will have a strong influence on the EPR particle size and dispersion. Combination of Mw morphology and a given EPR e.g. ICP (B) does always correlate with basic mechanical properties based on the EPR particles size, dispersion, etc. It is noted that the grades are made from Ziegler-Natta catalyst, which are affecting the Mw and Mn of the final blend when comparing to those made from Metallocene catalyst [25].

2.2 Methods

2.2.1 Blends preparation

ICP/HPP was mixed at the same weight percentage (Wt.%). The second mixing is ICP/ICP which was mixed at different weight percentage. The sample blends ratio (wt.%) and codes are displayed in **Table 3**. The ICP/HPP blends are identified by the abbreviations AE₂₅, BE₂₅, DE₂₅, AF₂₅, BF₂₅, DF₂₅, AG₂₅, BG₂₅, and DG₂₅, while ICP/ICP blends identified as AD₇₅ and BD₇₀, where A, B&D denote the various virgin ICP grades and the subscripts denote the weight percentage of HPP (E, F, G) for ICP/HPP, and weight percentage of ICPD in the blends for ICP/ICP. ICP/HPP and ICP/ICP blends were first blended using a Henschel mixer before undergoing the complete

compounding, pelletizing, and injection molding processes to produce finished components and samples for laboratory testing and analysis. The Henschel mixer 3Kg capacity and Barrel Maximum temperature 120°C was used in this study. The blended then compounded further by co-rotating Compounder Twin Thermofischer type (Twin extruder pelletizing machine), screw diameter 24 mm, L/D 40, with 10 zones started from 180-225 °C. The material passes a cold bath before goes to the Thermofischer pelletizer machine speed capacity 150 rpm and 220-250 °C, the output capacity is 3kg/h. The obtained samples of blended materials feeds into the hopper of KRAUSS MAFFEI injection molding machine, with clamping force 800KN, screw diameter 30 mm, screw speed 80 rpm, injection speed 50 cm³/s, injection time 1.7s, holding pressure 750 bar, cooling & holding time 15s, zones temperature 180 - 200°C, nozzle temperature 210°C and Barrel Capacity 115cc, melt temperature 220° C and injection rate is 300 mm/s. Izod impact, tensile strength at yield, tensile strength at break, tensile elongation at yield, tensile elongation at break, flexural strength, flexural modulus, Melt index (MI), Heat Deflection Temperature (HDT), Differential Scanning Calorimetry (DSC), and Scanning Electron Microscopy (SEM) were used to analyze the prepared parts/samples from injection molding in laboratories.

2.2.2 Preparation of test specimens

The injection molding KRAUSS MAFFEI machine used to create the test specimens for testing was described in section 2.2.1. According to ASTM D638, specimens for the dumbbell test were created to measure tensile qualities such tensile strength at

yield, tensile strength at break, tensile elongation at yield, and tensile elongation at break. According to ASTM D 790, flexural strength and modulus measurements were made. Izod impact was performed in accordance with ASTM D 256, and HDT specimens were created in accordance with ASTM 648. Also, the utilized injection molding machine is capable of working with any thermoplastics, including PE, PP, PS, PC, and others.

2.2.3 Thermal testing

According to ASTM D 1238-10 standard, ZWICK 4106 model MI-3 equipped with 1.2 to 50 kg load, 23 to 350°C, was used to determine the thermal characteristics data for melt index (MI). The weight in gm/10 min is determined by the test, which was run at 230 °C with a load of 2.16 kg. The CEAST testing machine, which has six stations and a temperature range of 25 to 175°C and a load of 1820 kPa, was used to measure the Heat Deflection Temperature (HDT) properties of the bars that were produced in accordance with ASTM D 648 and placed beneath the deflection measurement device. Each specimen is given an 1820 kPa load. The samples are then lowered into a silicone oil bath, which is heated at a rate of 2 °C per minute until the specimens deflect by 0.25 mm. The test method and sample are carried out in accordance with ASTM D 3418 to produce T_m, T_c, T_g and Crystallization %. The Differential Scanning Calorimetry (DSC) properties values are obtained using TA instrument, which can measure transitions from -90°C to 450°C. DSC measurement was performed using instrument from TA Q2000. A sample of 5 mg was placed into a closed pan and then placed in a temperature controlled chamber. Another empty pan

was used as a reference. The typical run involves heating/cooling of sample at controlled steady rate, and monitoring the heating flow to determine the phase transitions and/or cure reaction as function of temperature. The test was carried out based on the heating-cooling-heating principle, using temperatures from 50°C to 200°C. All required data of T_m, T_c and crystallization% have been obtained and recorded.

2.2.4 Mechanical testing

Using a universal testing machine (Zwick universal testing machine) outfitted with a 10 kN load cell and a contact laser Extensometer, the mechanical properties values of tensile strength@ yield, tensile strength @break, tensile elongation @ yield, and tensile elongation@ break were obtained. This was done in accordance with ASTM D638. The test was carried out at room temperature with a 50mm/min test speed. Using the same tensile machine, three-point bending tests were performed in accordance with ASTM D 790 standard at a thickness of 3.2 + 0.4 mm, a span length of 51.2 mm, and a cross head displacement rate of 1 mm/min to determine the results for flexural modulus and strength properties. According to ASTM D 256 standard, the Izod impact notched samples test is performed on specimens using a Zwick instrument impact pendulum with an overall impact energy of around 44 J. For each sample, at least five replicates were used to compute the average for each of the reported values.

2.2.4 Specimens Surface morphology

ICP mixes' morphology, structure, dispersion, and fracture mode were studied using scanning electron microscopy (SEM) using the FEI Quanta 200 with EDAX Octane Elect Su-per. By fastening the samples to 12.5 mm Al SEM stubs, the samples were made ready. The samples received a 60–120 second carbon sputter coating. After that, samples were examined using a SEM FEI Quanta 200 set to the following parameters: 20 kV for the accelerating voltage, 10 mm for the working distance, 5.0 for the spot size, and 1024 x 884 for the image resolution. Backscattered imaging mode was used to capture the images. The generated image provides a good indication of the distribution of particle sizes and the dispersion of the rubber.

3. Results and Discussion

The objective of this study is to improve the impact strength/resistance of selected Impact Copolymer Polypropylene (ICP) grades A, B, and D by blending them with each other and with selected Homopolymer Polypropylene (HPP) grades E, F,

and G. Table 1 and 2 present the characteristics of the utilized ICP and homopolymer grades in this investigation. These grades vary in fundamental properties, including melt flow, rubber composition, and performance characteristics.

Table 1. Virgin ICPs and HPP grades & coding

Material codes	Material Grades	Grade Type
A	48MK40	ICP
B	57MNK10	ICP
D	FPC75	ICP
E	PP500P	HPP
F	PP518A	HPP
G	PP519A	HPP

Table 2. characterization of virgin ICPs &HPP materials used in this study/work

Characterizations	Polymer materials					
	48MK40 (A)	57MNK10 (B)	FPC75 (D)	PP500P (E)	PP518A (F)	PP519A (G)
^a Izod Impact (J/m) Notched @23°C	96.72	118.47	45.47	25	30	-
^b Tensile str. @ yield(MPa)	26.9	24.22	26.74	35	32	30
^b Tensile str. @ break(MPa)	17.56	16.22	21.1	-	-	-
^b Tensile elon. @ yield(%)	4.1	4.64	3.98	10	12	10
^b Tensile elon. @ break(%)	53.2	100.6	12.8	-	-	-
^c Flexural modulus(MPa)	1234	1055	1189	1500	1550	1500
^c Flexural strength(MPa)	36.88	32.24	36.76	-	-	-
^d MI (g/10min)@Load 2.16 kg, Temperature 230 °C	16.743	12.727	73.463	3	25	35
^e DSC (Tm °C)	164.31	164.53	163.68	-	-	-
^f HDT(°C)@ 1820 kPa	98.8	89.87	98.2	100	118	100
Mw	211400	185300	156600	400000	220000	168213
Mn	48500	41700	24310	64500	32000	50201
C2 (Wt.%)	7.69	7.82	7.03			
EPR (Wt,%)	15	16	15			

^aASTM D256, ^bASTM D 638, ^cASTM D790, ^dASTM D 1238-10, ^eASTM D3418, ^fASTM D648

This study's goal was realized using a unique strategy that involved combining a specific component of HPP, E, F, and G with ICPs of grades A, B, and D, respectively, as well as a combination of different ICP of grades A, B and D with each other, at 25 wt. % of virgin ICPA with virgin ICPD,

and 30 wt.% of virgin ICPB with virgin ICPD. The blending ratios and coding for each mix are shown in Table 3. In the case of an injection application, the blend might be made either dry or melt

Table 3. Blending formulation & coding

Formulations	Blends ratio	Blends Code
ICP/HPP	A(75)E(25)	AE ₂₅
	B(75)E(25)	BE ₂₅
	D(75)E(25)	DE ₂₅
	A(75)F(25)	AF ₂₅
	B(75)F(25)	BF ₂₅
	D(75)F(25)	DF ₂₅
	A(75)G(25)	AG ₂₅
	B(75)G(25)	BG ₂₅
	D(75)G(25)	DG ₂₅
ICP/ICP	A(25)D(75)	AD ₇₅
	B(30)D(70)	BD ₇₀

3.1 Mechanical testing results

3.1.1 Impact strength/resistance

The first series of blends made from ICP/HPP. The ICP (A, B&D) blended with PP homopolymer E, F&G was found to have a negative effect on Impact strength, which was reported in Table 4, Figure 1. This could be attributed first to the lower impact strength of the homopolymer polypropylene and to the type of homopolymer, disordered rubber immiscibility in the ICP matrix, and the homopolymer's "fault" of acting as a stress concentrator agent. In the second series of blends made from ICP/ICP, the blends of ICP(AD75) and ICP(BD70), when compared to the virgin ICP(A), ICP(B), and ICP(D), exhibit a noticeable enhancement and increased resistance in impact strength. This improvement can reach up to 52% in

blends ICPAD75 and 20% in blends ICPBD70, surpassing the values of the virgin ICP(D). This enhancement is attributed to the miscibility of ICP(A) and ICP(B) materials in the ICP(D) matrix, facilitating rubber dispersion and molecular morphology in the ICP(D) matrix, which will be discussed in more detail in Section 3.3 (Figure 15).The improvement can be elucidated by the fact that mechanical properties are influenced by the ethylene-propylene random copolymer (EPR) rubber content, particle size, and dispersion/distribution [26]. Moreover, this affirms that specific properties, such as impact strength of the final blend, strongly depend on the polymer processability in terms of the molecular composition of both the continuous and discontinuous phases.

Table 4. Impact strength/resistance characterization for blends of ICP(A), ICP(B)& ICP(D) /E, F&G

Characterization	Polymer materials			
	ICP (A) blends			Virgin ICP(A)
	AE	AF	AG	48MK40 (A)
^a Impact (J/m) Notched @23°C	63.9+/-7.3	54.9+/-6.79	75.6+/-12.81	96.7+/-4.37
		ICP (B) blends		Virgin ICP(B)
	BE	BF	BG	57MNK10 (B)
^a Impact (J/m) Notched @23°C	61.45+/-4.77	63.9+/-5.18	66.2+/-4.15	118.4+/-11.17
		ICP (D) blends		Virgin ICP(D)
	DE	DF	DG	FPC75
^a Impact (J/m) Notched @23°C	47.4+/-9.81	40.1+/-7.51	33.1+/-3.05	45.5+/-6.24
ICP(AD75) & ICP(BD70)				
	Virgin ICP(A) 48MK40		Virgin ICP(D) FPC75	ICP(AD ₇₅)
^a Impact (J/m) Notched @23°C	96.7+/-4.37		45.5+/-6.24	69+/-7.46
	Virgin ICP(B) 57MNK10		Virgin ICP(D) FPC75	ICP(BD ₇₀)
^a Impact (J/m) Notched @23°C	118.4+/-11.17		45.5+/-6.24	54.4+/-3.92

^aASTM D256

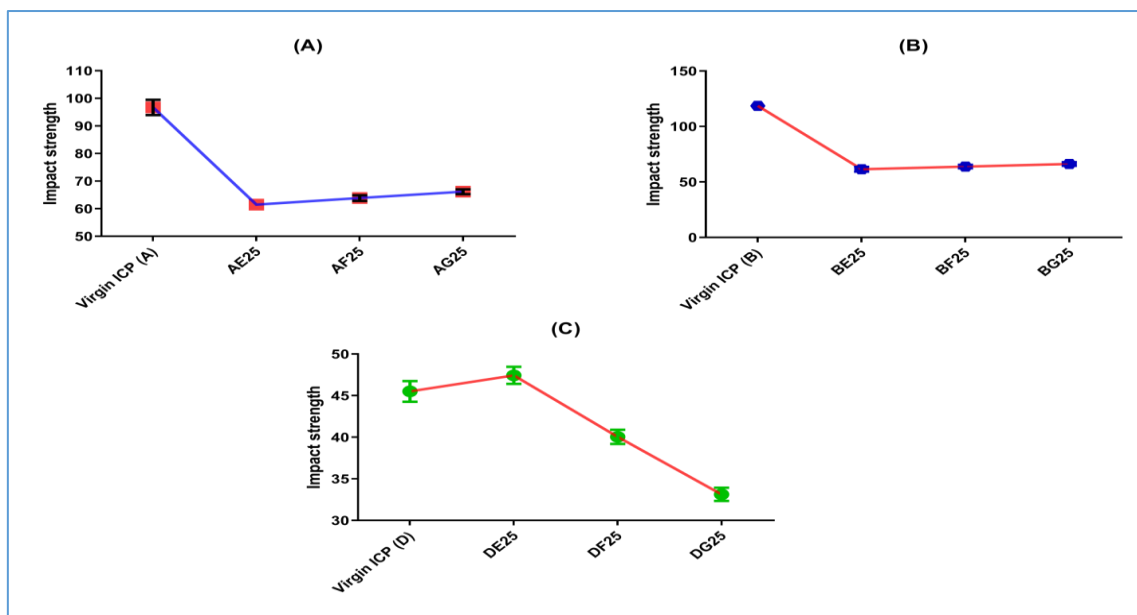


Figure 1: Impact strength (J/m) of blends (a) ICP (A)/E, F&G vs. virgin ICP(A) ;(b) ICP (B)/E, F&G vs. virgin ICP(B) ; (c) ICP (D)/E, F&G vs. virgin ICP(D)

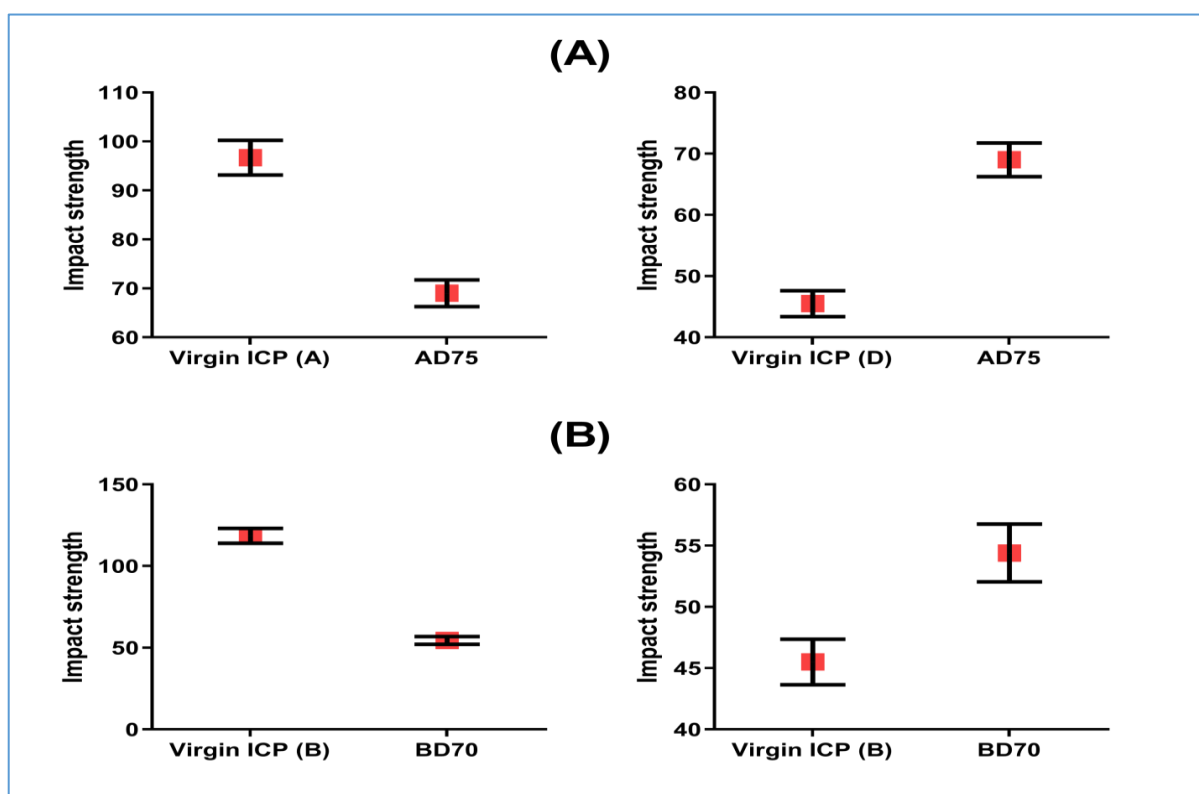


Figure 2: Impact strength (J/m) of blends (A) ICP(AD75) vs. Virgin ICP (A) & ICP (D) ; (B) ICP(BD70) vs. Virgin ICP (B) & ICP (D)

3.1.2 Tensile properties

The tensile properties of the mixes under investigation are shown in Figures 3 and 4, with more specific details found in Table 5 of the supplemental section. The tensile characteristics of the ICP/HPP blends mostly held true for all formulations. Blends DE25 and AG25, on the other hand, showed increased elongation at break. On the other hand, these characteristics decreased in mixes BE, BF, and BG. The reason for this alteration is because homopolymer E, which acts as a stress concentrator and increases stiffness while

decreasing elongation at break, was added to the virgin ICP(B) at a weight percentage of 30%. With respect to the ICP/ICP blends, blends ICPAD75 and ICPBD70 showed almost the same tensile characteristics as virgin ICPA and ICPD, with the exception of a little increase in tensile strength at break. Nonetheless, there was a noticeable decrease in elongation at break. Similar to the virgin ICP(D), these blends had no discernible effects on the tensile properties other than an increase in the percentage of elongation at break..

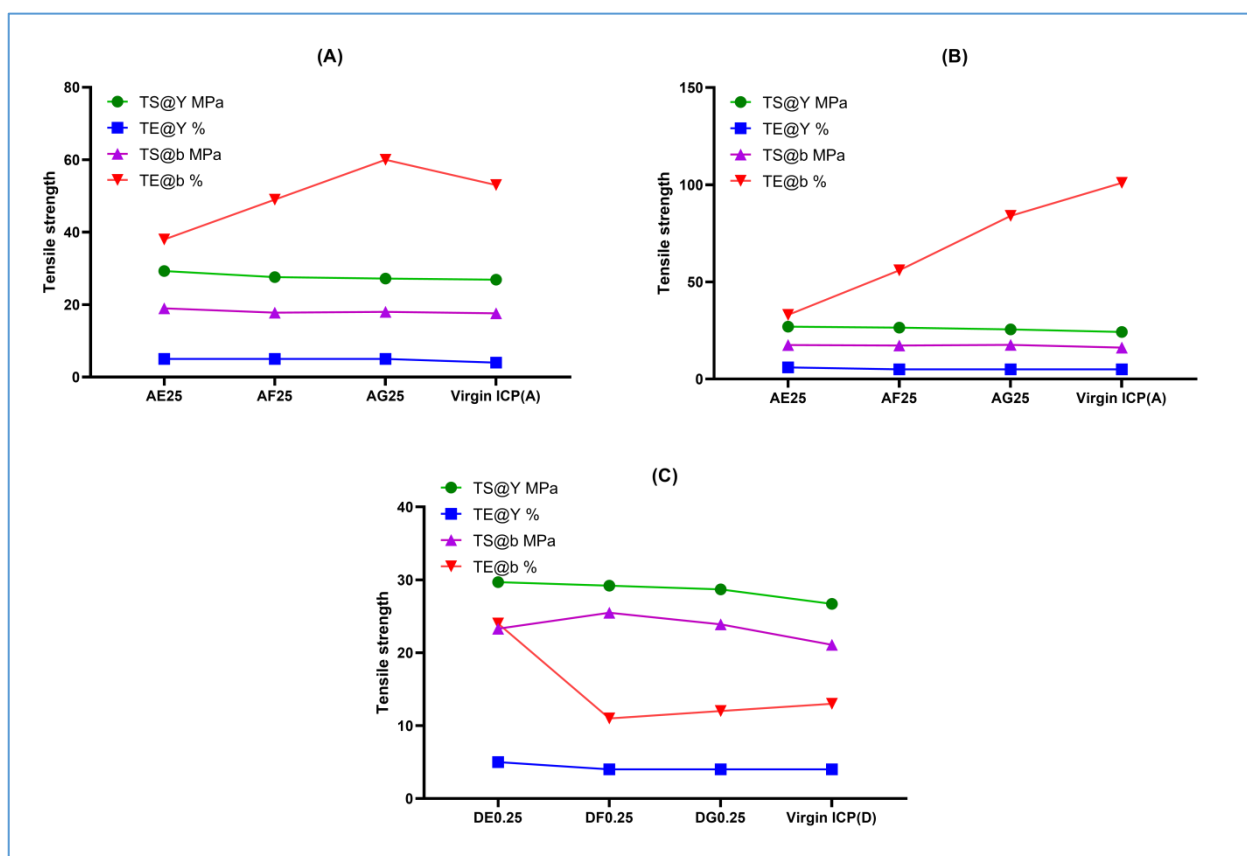


Figure 3: Tensile properties of blends (a) ICP (A)/E, F&G vs. virgin ICPA;(b) ICP (B)/E, F&G vs. virgin ICPB;(c) ICP (D)/E, F&G vs. virgin ICPD

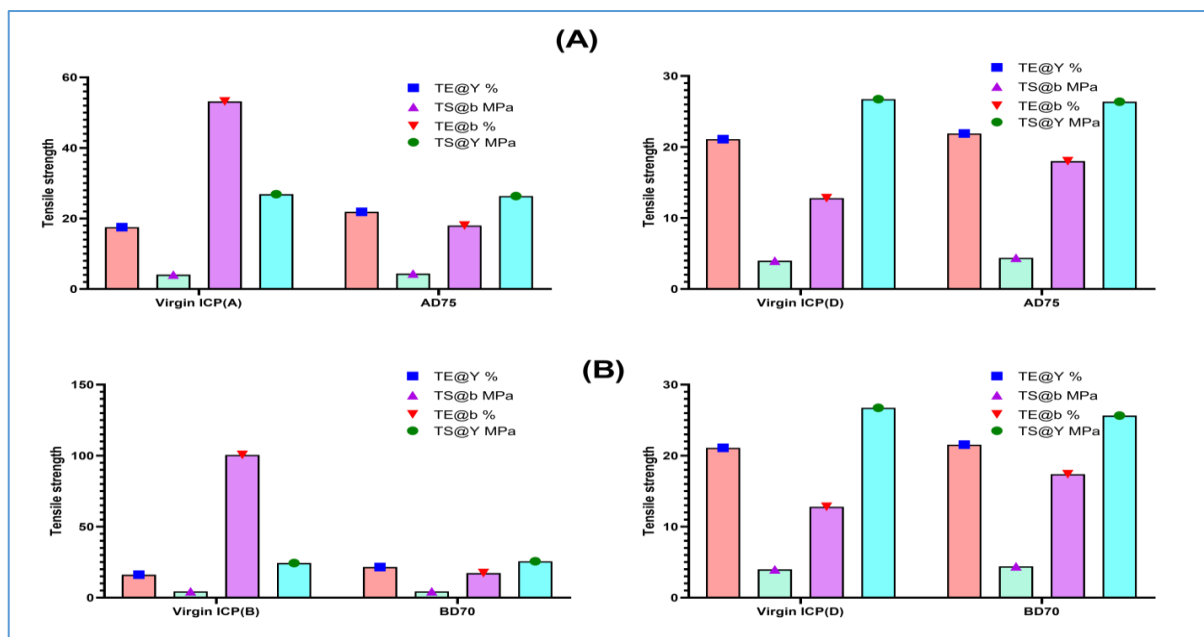


Figure 4: Tensile properties of blends (A) ICP(AD75) vs. Virgin ICP (A) & ICP (D);(B) ICP(BD70) vs. Virgin ICP (B) & ICP (D). Where TS@Y= Tensile strength @yield; TS@b= Tensile strength @break; TE@Y= Tensile elongation@yield;TE@b= Tensile elongation @break

3.1.2 Flexural properties

Figure 5 displays the flexural properties results for all blends involving ICP A, B, and D with HPP E, F, and G. Additionally, Figure 6 showcases the DD

blends ICPAD75 and ICPBD70, and further details are available in Table 6 within the supplementary information.

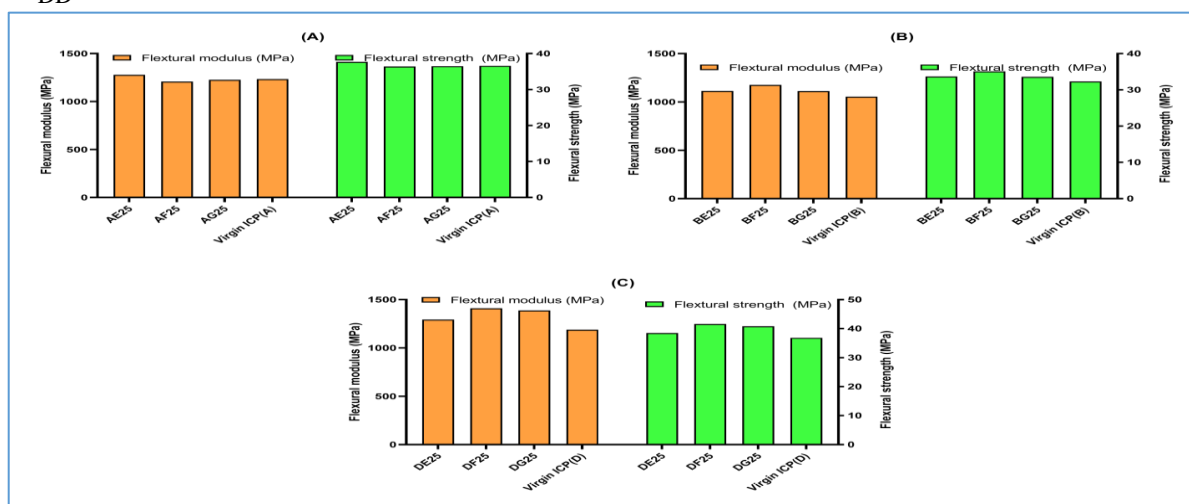


Figure 5: Flexural modulus & strength(MPa) of blends (A) ICP (A)/E, F&G vs. virgin ICP(A);(B) ICP(B)/E, F&G vs.virgin ICP(B);(C) ICP (D)/ E, F&G vs. virgin ICP(D)

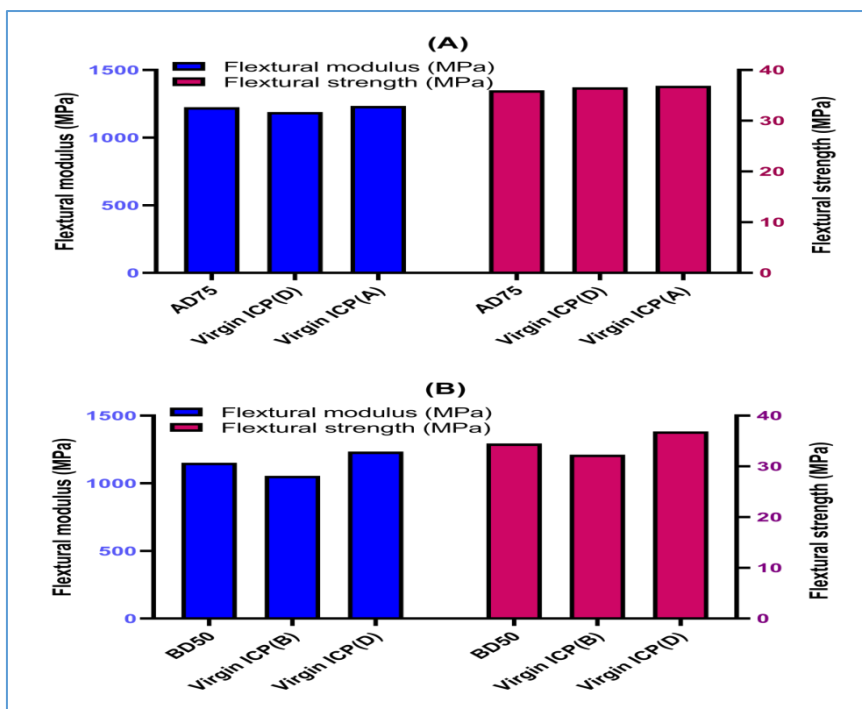


Figure 6: Flexural Modulus & Strength (Mpa) of blends (A) ICP AD₇₅ vs. virgin ICP(A) & (D); (B) ICP BD₇₀ vs. virgin ICP(B) & (D)

The findings related to the first series of blends incorporating ICP/HPP are presented in Figure 5 (Table 6 in the supplemental material). The blends of ICP(A&B) with HPP (E, F, and G) display comparable flexural strength to the virgin ICP (A, B), and there is no discernible difference in the flexural modulus for ICP(A)/HPP (E, F&G). Nevertheless, there is a slightly greater flexural modulus observed for ICP(B)/HPP (E, F&G).

In contrast, blends of ICP(D) with E, F, and G exhibit higher strength and flexural modulus. The rubber "EPR" particles appear to encircle the resin particles, in addition to embedding themselves in the homopolymer matrix.

The remarkable miscibility/diffusion of the additional homopolymer in the EPR area, combined with the effective particle distribution and dispersion of the rubber within the ICP(B) and ICP(D) matrix, significantly influences the morphology of the dispersed particles, impacting their size and shape (Figure 15).

As compared to virgin ICP(B) & ICP(D), the second series of blends, notably ICP(BD₇₀), showed no appreciable variations in flexural strength in Figure 6. On the other hand, the flexural modulus was higher than that of virgin ICP(B) and lower than that of ICP(D).

In contrast, there were no appreciable changes in flexural strength for blends including ICPAD₇₅ when compared to virgin ICP(A) & ICP(D).

However, there was a noticeable rise in flexural modulus when compared to virgin ICP(D) and no change when compared to virgin ICP(A), staying almost the same. In a similar vein, the rubber "EPR" particles in ICP(D) looked to encircle the resin particles in addition to appearing entrenched in the ICP(A) and ICP(B) matrix.

However, the remarkable miscibility/diffusion of the extra ICP(A) and ICP(B) in the EPR region, along with the rubber's dispersion and effective particle distribution within the ICP(AD75) and ICP(BD70) matrix, had a substantial effect on the dispersed particles' morphology, influencing their size and shape (as shown in Figure 9).

Statistical software with a package supporting Design of Experiments (DOE) was employed in the experimental setup. Response factors included key characteristics affecting product quality, such as impact strength and stiffness. Control variables were contingent on the types of High-Performance Polypropylene (HPP) and Impact Copolymer Polypropylene (ICP) utilized in the raw material (Virgin ICP). To identify the pivotal factors influencing product quality, eleven tests were conducted, utilizing statistical prediction models.

In contrast to the blends formed from ICP blends, the projections indicated that the blend incorporating HPP as a minor phase did not yield an increase in impact strength. The optimal results highlighted that the improvements observed with ICP(AD75) and ICP(BD70) are governed by the

molecular weight and particle structure of the minor phase, as reflected in the Melt Flow Index (MFI) and impact polymer of the virgin-based grades.

3.2 Thermal properties

3.2.1 Melt index (MI)

A comprehensive comparison of various blends is shown in Figure 7, with a focus on the melt flow indices (MI) in relation to the virgin ICP requirements listed in Table 7 of the supplemental material. The blends of virgin ICP(A&B) with homopolymer polypropylene F&G grade exhibited a minor rise in the MI in the first series of blends including ICP/HPP; this was probably because PP518A & PP519A had the highest MI values. Conversely, mixes prepared from virgin ICP(A&B) and grade E homopolymer, as well as mixes from virgin ICP(D) and HPP E, F&G, showed somewhat lower MI values than the virgin ICPs.

Therefore, it would appear acceptable to conclude that the differences between the MI data and the specification are not noticeably more significant. The melt indices of blends ICP(AD75) & ICP(BD70) in the second set of blends containing ICP/ICP exhibited similar behavior.

In contrast to virgin ICP(A) and ICP(B), these blends demonstrated an increase; however, when compared to virgin ICP(D), a decrease was observed. This variance may have been influenced by the highest Melt Index (MI) value of virgin ICPD, as illustrated in Figure 8

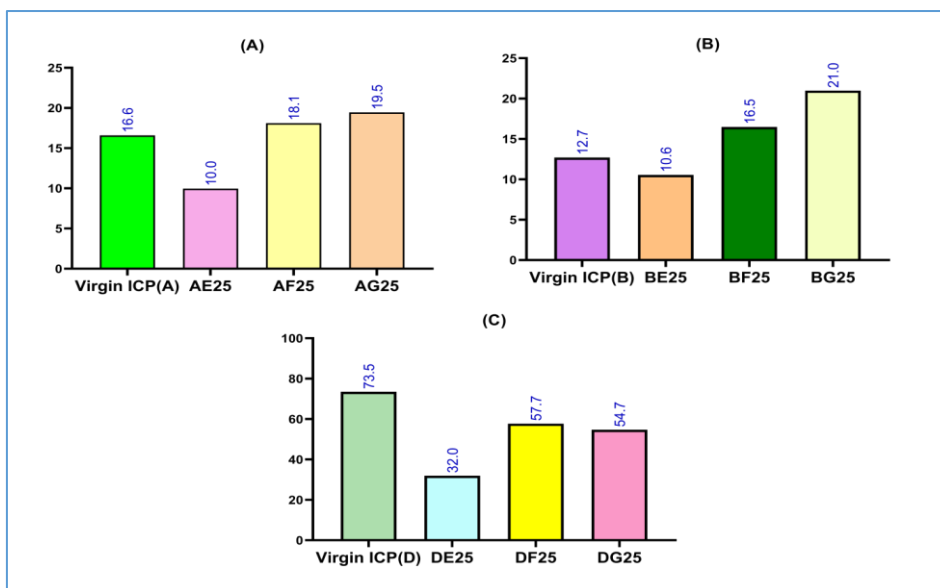


Figure 7: Melt indexes (MIs) of blends (A) ICP (A)/E, F&G vs. virgin ICP(A) (B) ICP (B)/E, F&G vs. virgin ICP(B);(C) ICP (D)/E, F&G vs. virgin ICP(D)

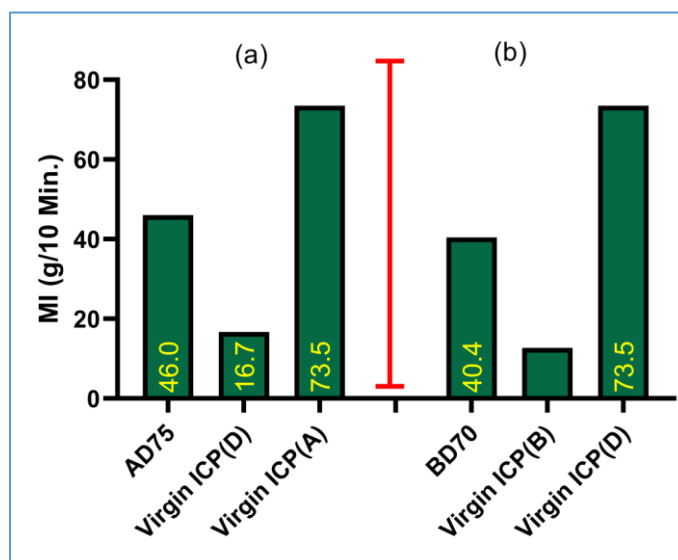


Figure 8: MI (g/10 Min.) of blends (a) ICP AD75 vs. virgin ICP(A) & (D); (b) ICP BD70 vs. virgin ICP(B) & (D)

3.2.2 Heat Deflection temperature (HDT)

Figure 9 displays the Heat Deflection Temperature (HDT) data for the first series of Impact Copolymer Polypropylene (ICP)/Homopolymer Polypropylene (HPP) blends, while Figure 10 illustrates the HDT data for the second series of ICP/ICP blends (Table

8 in the supplemental information). HDT levels are lower in ICP/HPP blends than in any of the individual virgin ICPs. The HDT is consistently lower for all ICP/HPP blends compared to the virgin blends, and the decrease is approximately the same for all combinations. This suggests a

noticeable distinction between ethylene and propylene regarding their glassy transition temperatures. However, the second series of ICP/ICP blends indicates that the HDT is almost as

low as that of the virgin blends and is in the order of ICP/HPP, suggesting that molecular composition also influences HDT.

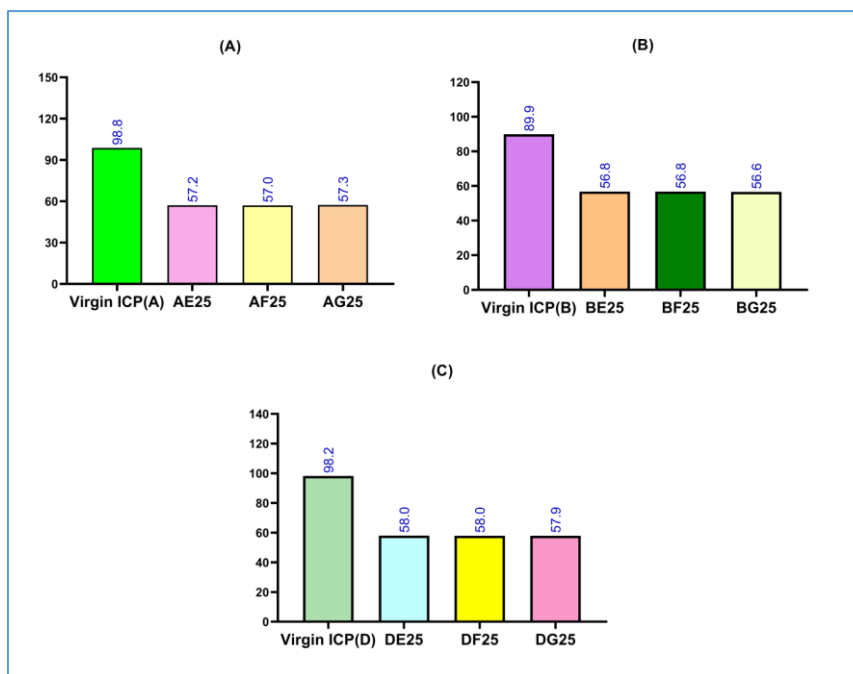


Figure 9: HDT blends (A) ICP AE25, AF25 & AG25 Vs. virgin ICP A; (B) ICP BE25, BF25 & BG25 Vs. virgin ICP B; (C) ICP DE25, DF25 & DG25 Vs. virgin ICP D

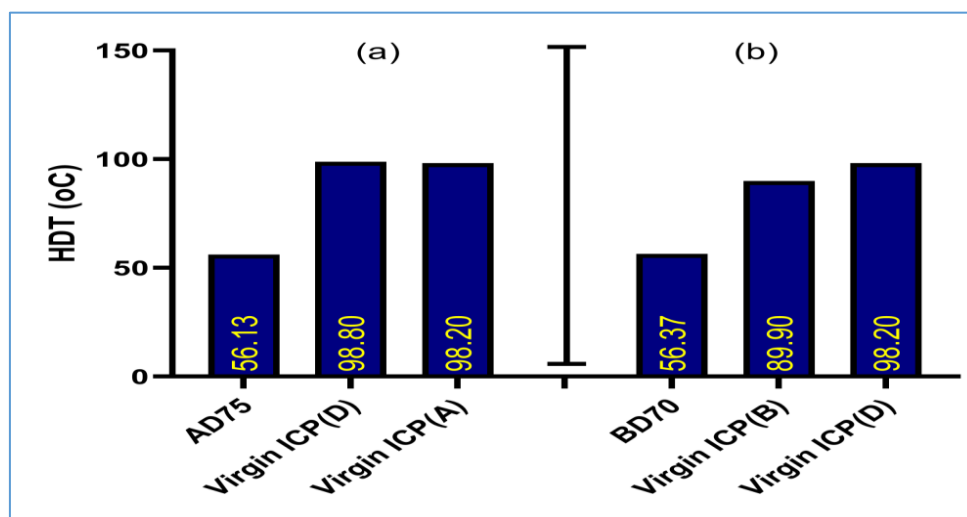


Fig. 10 . HDT (°C) of blends (a) ICP AD₇₅ vs. virgin ICP(A) & (D); (b) ICP BD₇₀ vs. virgin ICP(B) & (D)

3.2.2 Different scanning calorimetry (DSC)

The melting temperatures, as measured by thermograms and thermal characteristics using the Differential Scanning Calorimetry (DSC) technique, are presented in Figure 11, 12, 13, and 14 (Table 9 in the supplementary information). The thermograms and thermal properties, according to

the DSC method, did not exhibit significant differences in melting and crystallization temperatures (Figure 11 & 13). However, there is a decrease in crystallinity in blends made from F&G as a discontinuous phase and a relatively slight drop in blends made from E as a discontinuous phase.

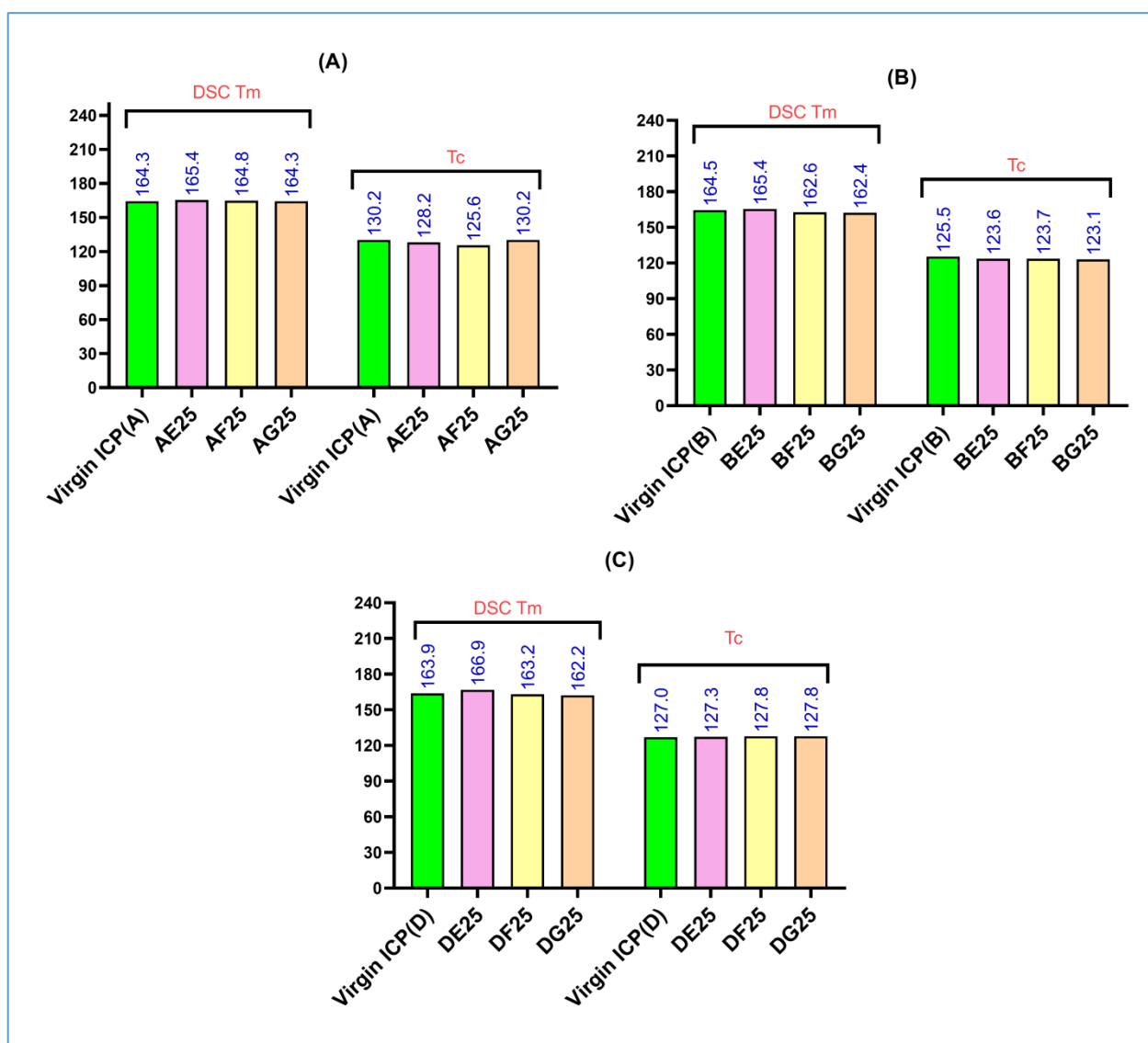


Figure 11: DSC Tm & Tc (°C) of blends (A) ICP (A)/E, F&G vs. virgin ICP(A) ;(B) ICP (B)/E, F&G vs. virgin ICP(B); (C) ICP (D)/E, F&G vs. virgin ICP(D)11

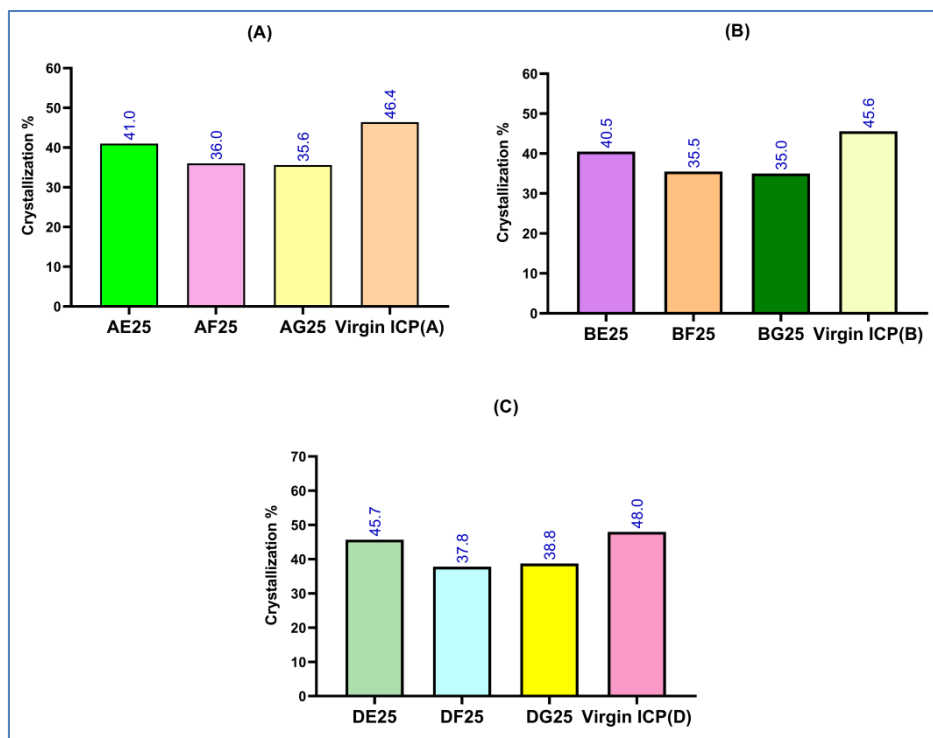


Figure 12: Crystallization % of blends (A) ICP (A)/E, F&G vs. virgin ICP(A);(B) ICP (B)/E, F&G vs. virgin ICP(B); (C) ICP (D)/E, F&G vs. virgin ICP (D)

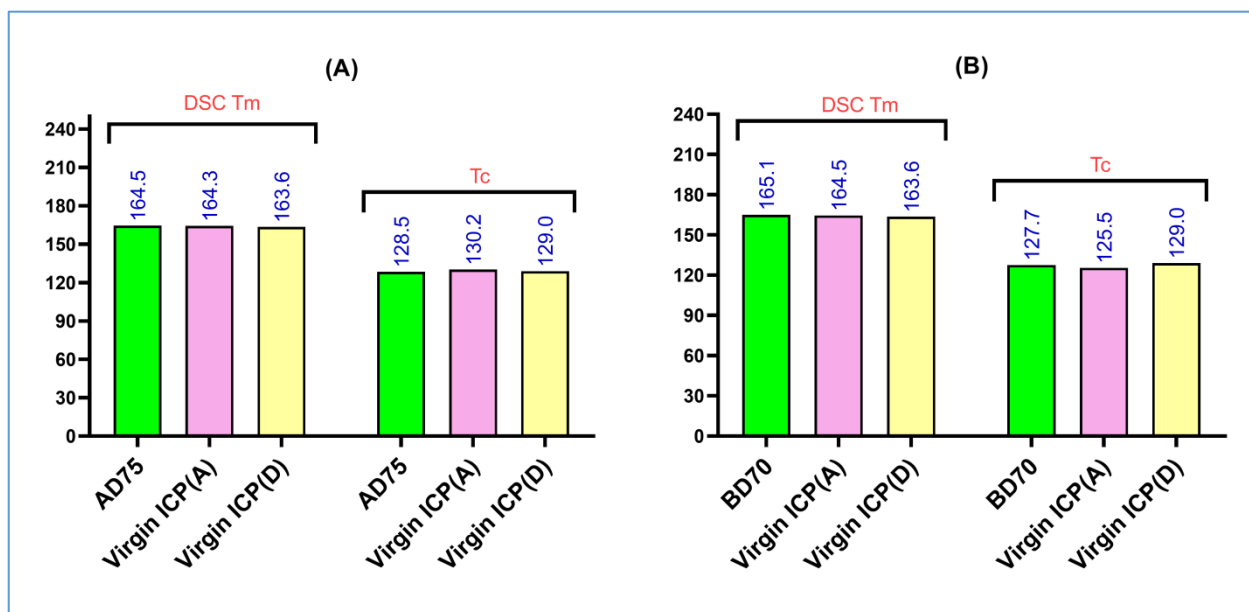


Figure 13: DSC Tm & Tc (°C) of blends (d) ICP AD₇₅ vs. virgin ICP(A&D) ;(e) ICP BD₇₀ vs. virgin ICP(B&D)

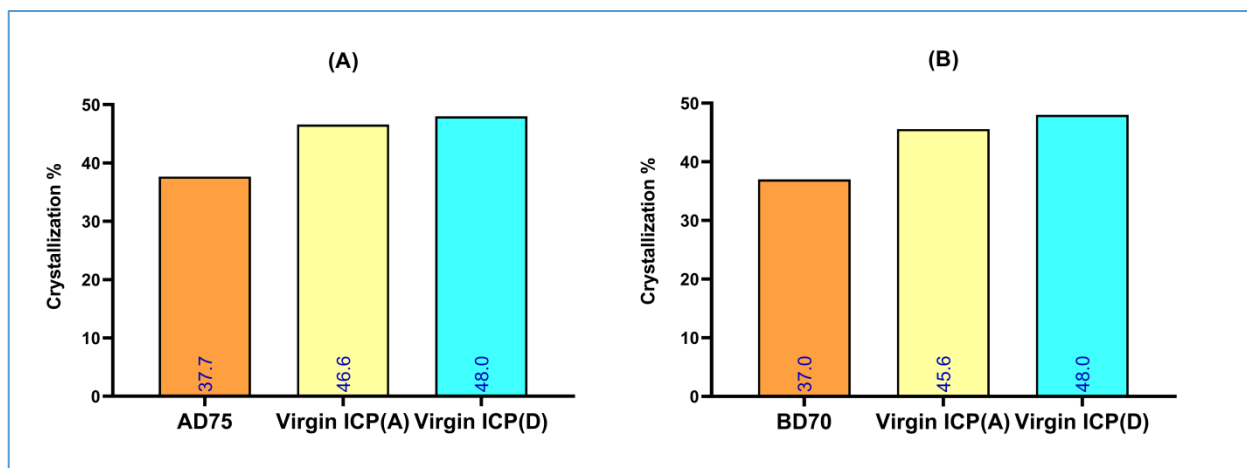


Figure 14: Crystallization % of blends (d) ICPAD₇₅ vs. virgin ICP(A&D);(e) ICPBD₇₀ vs. virgin ICP(B&D). Where (T_m °C) = Melting temperature, T_c= Crystallization temperature

The observed improvements in impact resistance with the incorporation of a rubber mixture in the ICP matrix can be attributed to several underlying mechanisms. Firstly, the rubber particles act as energy dissipaters and absorb the impact energy, preventing its propagation through the material. This absorption of energy reduces the stress concentration and prevents crack propagation, resulting in enhanced impact resistance. Secondly, the uniform distribution of rubber particles within the ICP matrix plays a crucial role in improving impact resistance. A uniform dispersion ensures that the impact energy is efficiently absorbed and dissipated throughout the material. It prevents the formation of localized weak regions and enhances the overall toughness of the blend. The uniform size distribution of the rubber particles further contributes to the homogeneity of the material and reduces the probability of stress concentration points. Blending different grades of ICP also has a significant effect on the mechanical properties, including impact resistance. The use of different grades allows for tailoring the properties of the blend according to specific requirements. For example, blending ICP grades with varying EPR content can help optimize the balance between impact resistance and other mechanical properties. Higher EPR content generally improves impact resistance, while lower EPR content enhances stiffness and tensile strength. By carefully selecting the proportions and characteristics of the different ICP grades, it is possible to achieve a synergistic

effect and enhance the overall performance of the blend. Moreover, blending different grades of ICP can influence the interfacial adhesion between the phases and impact the dispersion of the rubber particles. Optimal interfacial adhesion ensures efficient stress transfer between the phases and prevents the debonding of rubber particles during impact loading. This interfacial adhesion can be influenced by factors such as the compatibility of the polymer matrices, the presence of compatibilizers or coupling agents, and the processing conditions. A strong interfacial adhesion and well-dispersed rubber particles contribute to the overall improvement in impact resistance. It is important to note that the specific impact of blending different grades of ICP on the mechanical properties and underlying mechanisms may vary depending on the composition, morphology, and processing conditions. Further research and characterization techniques, such as microscopy and mechanical testing, can provide a more detailed understanding of the structure-property relationships and the contributions of different factors. Overall, the blending of different grades of ICP offers a versatile approach to tailor the mechanical properties, including impact resistance, of the resulting blend. The underlying mechanisms, including energy absorption, uniform dispersion, and interfacial adhesion, play critical roles in enhancing the impact resistance of the material. Further investigations into the microstructure, interfacial interactions, and processing parameters

will contribute to a deeper understanding and optimization of these compounding approaches.

3.3 Scanning electron microscopy (SEM).

The assessment of interface adhesion in multiphase materials frequently necessitates the examination of fractured surfaces via micrographs. The surfaces are illustrated in Figure 15, which highlights significant variations in the rubber particle diameters of the virgin ICP (D) in comparison to ICP (A) and ICP (B). The reduced dimension of the rubber particulates in the virgin ICP(D) is emphasized in Parts a, b, c, d, and e. On the contrary, the micrograph illustrates that the EPR

particles are firmly affixed to the matrix and uniformly distributed in the composite composed of ICPAD75. Conversely, composites containing ICPBD70 exhibit reduced rubber particle size to the point where they are virtually undetectable; this characteristic corresponds to an increase in impact strength. This observation implies that the uniform dispersion and matrix anchoring of the EPR particles in blend ICPAD75 contribute positively to the material's properties. On the contrary, the increase in impact strength observed in composites containing ICPBD70 is accompanied by larger and less distinct rubber particulates [27].

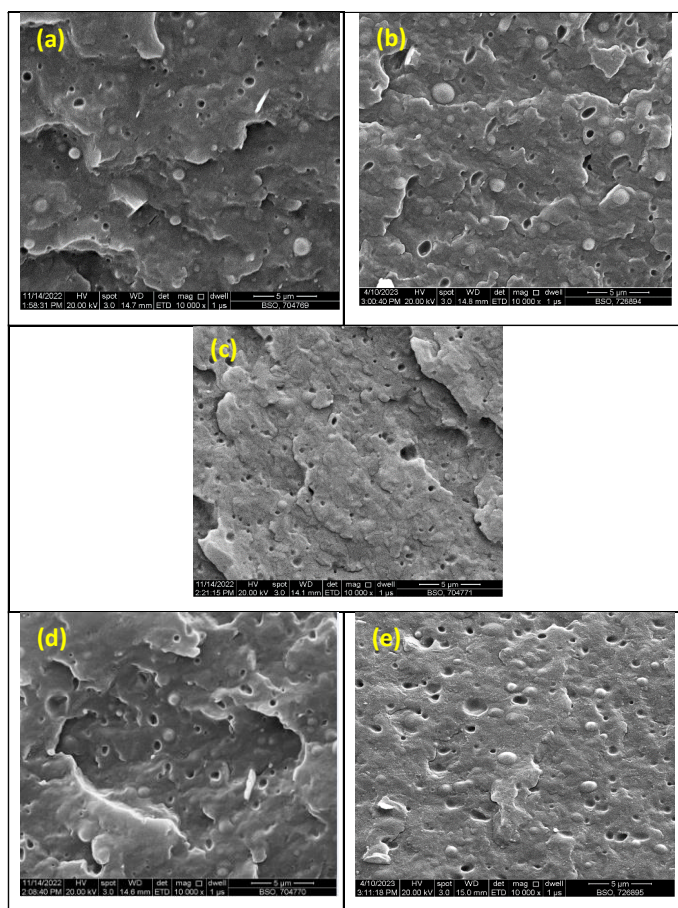


Figure 15: SEM images of (a) virgin ICP A; (b) blends ICP AD₇₅; (c) virgin ICP D; (d) virgin ICP B; (e) blends ICP BD₇₀

Conclusions

The absence of noticeable enhancements in the overall mechanical properties suggests that blending different grades of Impact Copolymer Polypropylene (ICP) with various Homopolymer Polypropylene (HPP) grades in the discontinuous phase did not yield the anticipated results. However, a noteworthy improvement in impact strength was observed when different ICP grades were blended as the non-continuous phase with ICP(D) at levels of approximately 25% and 30%. This improvement resulted in a remarkable 52% increase in impact strength compared to the original ICP(D) grade utilized as the continuous phase. The positive outcome appears to be attributed to a uniformly distributed rubber content and precisely controlled particle sizes, influenced by the molecular structure in specific blends. These findings underscore the significance of the distribution of rubber and the sizes of the particles as crucial factors contributing to substantial enhancements in impact strength.

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