

Compatibilization Strategies for Recycling Applications of High Impact Polystyrene/Acrylonitrile Butadiene Blends

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Abstract Plastic waste from electrical and electronic equipment (WEEE) is growing up exponentially fast during the last two decades, mainly due to short lifetime of technological products like cellphones or computers. This situation entailed an increase in the accumulation of specific plastic materials such Acrylonitrile–Butadiene–Styrene (ABS), High Impact Polystyrene (HIPS), Polycarbonate, among others. These plastics can be recycled by themselves but their separation by type is neither easy nor economically viable, then recycling them together as a blend is the most economically viable alternative. However, mechanical properties suffer a deterioration and to enhance phase adhesion and add value to this WEEE blend, an adequate compatibilization is needed. To choose a compatibilization route an accurate comprehension of blends behavior has to be done. In this work, a systematical study of the addition compatibilization of HIPS/ABS blends was performed. Besides results were focus to WEEE recycling, in order to comprehend this complex system, virgin base materials were used. Relative amount effect on self-compatibilization was analyzed by two different HIPS/ABS blends, one with major content of HIPS and other with major content of ABS. Also, two different copolymers were used as compatibilizer, Styrene–Acrylonitrile (SAN) and Styrene–Butadiene–Styrene and the concentrations chosen were 2 and 20 wt%. The best performance was achieved for blend with major content of

ABS by using 2 % of SAN, obtaining a compatibilized blend with a general improvement of mechanical properties specially toughness in a 350 % and elongation in a 77 % respect to the physical blend.

Keywords HIPS · ABS · Compatibilization strategies · WEEE

Introduction

Waste from electrical and electronic equipment (WEEE) stream is exponentially growing as constant advances and changes in technology production. For example, new generation cell phones are replaced in less than 2 years which means that an equivalent amount will be discarded and turned into e-scrap [1, 2]. In the worldwide, 49 % of those discarded cellphones are reused as what they are, 48 % are finally discarded or kept aside and only a 3 % are recycled [3]. This is an evidence of continue and constant increasing in mobiles phones contribution to WEEE, and they are just a piece of the total electrical and electronic devices used around the world. Junk technology is a set of wastes considered hazardous, from computers, cell phones, televisions and appliances in general, which has been consumed or discarded. Within WEEE plastic represent the 17 wt%. However, volume fraction is much higher because of their low density. Moreover, when they are final disposed, requires huge spaces due to parts shapes and elasticity. Also, their plastics raw materials are not cheap, then an adequate reuse or recycle would have multiple benefits [4, 5].

WEEE stream has different kinds of plastics all together. The best recycled resin could be obtain by separating each material by type, but separate them is neither technical nor

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economically viable [6, 7]. Then, an alternative would be recycling them together as a blend. It is well known that the direct blending of two or more polymers in appreciable proportion, causes phase segregation, low interfacial adhesion, and poor mechanical properties [8–12]. Therefore, a compatibilization treatment to improve phase adhesion, reduce interfacial tension, and phase stabilization by the inhibition of droplet coalescence, is needed. In particular, multiple phase blend compatibilization poses a quite complex problem particularly in controlling the different interphases involved [13, 14].

Most common plastics in electrical and electronic equipment are copolymers like Acrylonitrile–Butadiene–Styrene (ABS), High Impact Polystyrene (HIPS), Polycarbonate (PC), among others. Particularly, HIPS and ABS, that constitute the major fraction, have complex morphologies that depends on the relative amount of their components. Their properties are highly related with particle size and volume fraction of butadiene phase present in both copolymers [11, 15, 16]. Indeed, this phase seems to indicate that their blends could be “self-compatibilized”. However, previous results shows that when they are mechanically blended final material presents phase segregation [17, 18]. Particularly, Arnold et al. [19] claims that blends of virgin HIPS and virgin ABS phase separation depends on the relative concentration of the constituents of each copolymer among the relative concentration of HIPS and ABS. Properties suffer a deterioration respect on the base materials and consequently, final blend has poor added value [20, 21].

Within compatibilization methodologies, there are two ways that would be adaptably and usefully for actual processes. The first one includes a compatibilizer addition to melting blend (compatibilization by addition). Typical compatibilizers are copolymers with monomers present in each blend material or a combination of them. In this process, the compatibilizer is dispersed in one of the phases and during mixing get to the interphase, then compatibilization effectiveness hardly depends on the compounding process. The other compatibilization method, called in situ or reactive compatibilization, involves chemical reactions inside melted blend to generate copolymers in situ, crosslinking or functionalization of the base components. In this case the compatibilizer copolymer is generated in the interphase avoiding dispersion impediments during process, being generally more effective. However, for polymer recycling compatibilization, the addition of a third component is the most convenient method because of their easy processability, higher process control and lower cost respect on in situ compatibilization [11, 16, 20, 22].

Regarding plastic WEEE recycling and taking into account that ABS and HIPS are major components, an accurate comprehension of their blends behavior and

possible compatibilizers is the way to add value to this kind of recycled material. In literature there is no longer information about compatibilization of HIPS/ABS blends. Peydro Rasero et al. [23] use Styrene–Ethylene–Butadiene–Styrene (SEBS) as possible compatibilizer of virgin ABS and HIPS for the reason described before. Final results indicate an improvement in ductile properties with few loss in tensile strength.

In the present work, a systematical study of the addition compatibilization of HIPS/ABS blends is presented. Although results are focus to WEEE recycling, in order to comprehend this complex system and avoid spurious variables, virgin base materials are used. Effect of relative amount of HIPS/ABS on self-compatibilization is also analyzed, as well as the influence of two different copolymers as compatibilizer. Considering that ABS is a blend of Styrene–Acrylonitrile copolymer (SAN) and Polybutadiene (PB), pure SAN could be consider as compatibilizer because it contain styrene and acrylonitrile phase. Also Styrene–Butadiene–Styrene (SBS) was used as compatibilizer as its molecules includes butadiene and styrene blocks then could be associate with initial blend materials. In addition, special emphasis was done in compatibilizers concentration influence on flexural mechanical properties and blends morphology with the aim of mechanical properties improvement and add value to HIPS/ABS blends by a screening concentration study.

Experimental

Materials

HIPS Innova 4600 from Petrobras and ABS Teluran HI-10 from BASF were used as base materials of blends. SBS KIBITON[®] Q-Resin PB-5903 from CHI MEI CORPORATION and SAN Luran 348Q from BASF were used as compatibilizers of HIPS/ABS blends.

Blending

HIPS (80 wt%)/ABS (20 wt%) and HIPS (20 wt%)/ABS (80 wt%) physical blends were prepared under nitrogen atmosphere, in a batch mixer (*Brabender Plastograph W50*) at 180 °C and 30 rpm for 10 min. Compatibilized blends were prepared in the same batch mixer under the same condition as physical one. In order to make a screening test, two different concentration of each compatibilizer were chosen, one very low (2 wt%) and other bigger enough (20 wt%). In this way, 2 and 20 wt% of SAN and SBS to both physical blends. Table 1 summarizes the characteristics of all blends prepared.

Table 1 Names and concentration of all blends prepared

Name	HIPS/ABS (H/A) (wt%/wt%)	SBS (wt%)	SAN (wt%)
Physical blends			
H80/A20	80/20	0	0
H20/A80	20/80	0	0
Compatibilized blends			
H80/A20-2SBS	78.4/19.6 (80/20)	2	0
H80/A20-20SBS	64/16 (80/20)	20	0
H80/A20-2SAN	78.4/19.6 (80/20)	0	2
H80/A20-20SAN	64/16 (80/20)	0	20
H20/A80-2SAN	19.6/78.4 (20/80)	2	0
H20/A80-20SAN	16/64 (20/80)	20	0
H20/A80-2SAN	19.6/78.4 (20/80)	0	2
H20/A80-20SAN	16/64 (20/80)	0	20

Characterization

Mechanical Properties

Flexural tests were performed at room temperature in the *Universal Testing Machine Instron 3369*. Flexural specimens were cut from plates prepared by compression molding at 180 °C. Test conditions and specimen dimensions were determined according to *ASTM D790-03* standard for plastic. Eight specimens for each sample were measured. Modulus, ultimate strength and elongation at break were comparatively assessed from stress–strain curves.

Blends Morphology

Blends morphology analysis were performed by *scanning electron microscopy (SEM)* in a LEO EVO 40 XVP electron microscope, operated at 10 kV. Samples were cryo-fractured by immersion in liquid nitrogen, mounted on bronze stubs and then, coated with a gold layer ($\sim 30 \text{ \AA}$), using an argon plasma metallizer (sputter coater PELCO 91000).

Results and Discussion

Table 2 shows flexural mechanical properties (E , σ_u and ε_b) and toughness for base materials and compatibilizers, as well as for all physical and compatibilized blends. Note that according to *ASTM D790-03*, flexural test for thermoplastics materials takes a maximum elongation of 8 %, because that value is enough to corroborate the good performance of the material. Toughness is the energy per volume necessary for material break and it is calculated as the area under stress–strain curve up to break. In specimens that not break, it was calculated as the area under stress–

strain curve up to 8 % of strain. From these data, it is possible to note that both, HIPS and ABS do not break during test, and ABS has lower E and higher σ_u than HIPS, resulting ABS around 50 % tougher than HIPS.

The best evidence of good blend compatibilization is given by mechanical properties improvement. Variation in high strain properties like ultimate strength (σ_u) and elongation at break (ε_b) evidence phase adhesion changes, given a measurement of blend compatibilization effectiveness. It is important to note that the adhesion between phases is the most sensitive property to compatibilization. On the other hand, Young modulus (E) is a zero strain property and in the case of blends only depends on the internal structure of the species and relative concentration of the components being the less sensitive to compatibilization process.

Physical blends mechanical properties, as expected, suffer notable deterioration indicating poor phase adhesion and then, not self-compatibilization [19]. Because of this reason the addition compatibilization was studied. It is important to note that a good compatibilizer could enhance phase dispersion and distribution, phase domains reduction and phase adhesion improvements respect physical blends [9]. Then, a combined analyzes between mechanical performance and morphology of blends will give a quantification of the compatibilization effectiveness. In order to analyze the compatibilization efficiency all blends were subjected to flexural tests in three points. Then, to corroborate claims made from mechanical tests a morphological studied was performed.

Mechanical behavior of HIPS/ABS physical blends will depend on which, HIPS or ABS is the major component. Flexural properties of both blends suffer a deterioration respect on base materials, as expected. They lose more than 50 % of the ε_b given a first indication of poor interfacial adhesion. Regarding σ_u , in both cases show a negative deviation respect to the rule of mix prediction,

Table 2 Flexural mechanical properties for plastic base materials, compatibilizer copolymers and all blends prepared, according ASTM D790-03

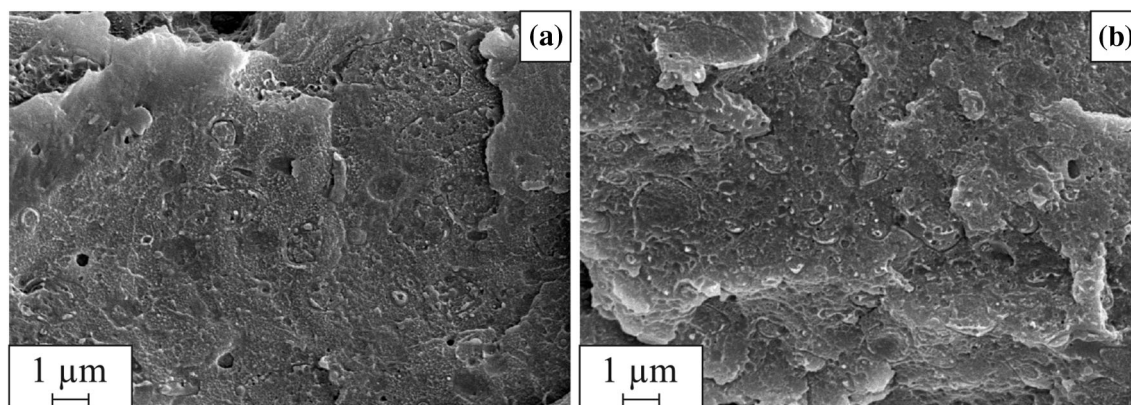
Sample	E (MPa)	σ_u (MPa)	ϵ_b (%)	Toughness (J/m^3)
HIPS	1914 \pm 173	33.4 \pm 1.1	Not break	2.14 \pm 0.07
ABS	1796 \pm 58	54.1 \pm 1.9	Not break	3.23 \pm 0.12
SBS	670 \pm 122	20.1 \pm 3.2	Not break	1.71 \pm 0.22
SAN	3234 \pm 186	79.8 \pm 7.9	2.25 \pm 0.67	1.08 \pm 0.15
H80/A20	1878 \pm 132	29.4 \pm 2.2	2.04 \pm 0.40	0.34 \pm 0.11
H20/A80	1613 \pm 70	40.6 \pm 4.2	3.46 \pm 1.22	0.56 \pm 0.04
H80/A20-2SBS	1811 \pm 75	28.2 \pm 1.9	1.84 \pm 0.16	0.30 \pm 0.05
H80/A20-20SBS	1442 \pm 85	30.4 \pm 3.5	5.69 \pm 1.38	1.66 \pm 0.36
H80/A20-2SAN	2042 \pm 146	32.6 \pm 3.1	2.17 \pm 0.35	0.44 \pm 0.11
H80/A20-20SAN	2213 \pm 108	37.1 \pm 1.5	2.27 \pm 0.13	0.52 \pm 0.06
H20/A80-2SBS	1684 \pm 182	38.0 \pm 8.0	2.73 \pm 0.70	0.65 \pm 0.24
H20/A80-20SBS	1204 \pm 37	33.3 \pm 1.1	Not break	2.01 \pm 0.13
H20/A80-2SAN	1757 \pm 31	47.1 \pm 0.7	6,14 \pm 1,27	2.51 \pm 0.65
H20/A80-20SAN	2124 \pm 44	54.8 \pm 1.3	6,32 \pm 1,09	2.93 \pm 0.68

corroborating that the adhesion is not good [24]. E of blend with major content of ABS does not follow rule of mix, presenting a negative deviation which also evidence deterioration in this property, this could be attributed to a possible acrylonitrile phase encapsulation by the rubbery phase. Toughness in both physical blends suffer a notable decreasing which is directly related with the global performance deterioration. On the other hand, E of blend with HIPS as major component is the only property which follows the rule of mix. These results show that there is not self-compatibilization of HIPS and ABS by direct mixing independently of which one is major component.

In Fig. 1, SEM micrographs of cryogenic fracture surface of all blends prepared are presented. Particularly, Fig. 1a, b shows SEM micrographs (20,000 \times) for physical blends, with major content of HIPS (H80/A20) and major content con ABS (H20/A80), respectively. By analyzing morphology of physical blends, it is possible to note that in both cases there are fragile fracture edges and wide

distribution of domain sizes. In the case of H80/A20 blend, domain size tend to be smaller than in the case of H20/A80 blend. In the last one there are some domains that evidence phase encapsulations, confirming claims made from mechanical behavior.

In order to enhance final properties of each physical blend, the use of two different copolymers as compatibilizers was analyzed. These copolymers were selected mainly for their similar structures with the main components of HIPS and ABS. In this way SBS and SAN were selected by contain styrene and butadiene blocks and styrene and acrylonitrile blocks, respectively. In the first case, better compatibilization of major HIPS phase blend is expected and in the second case, major ABS phase blends could be improved because of acrylonitrile component. In order to make a screening test, two different concentration of each compatibilizer were chosen, one very low (2 wt%) and other bigger enough (20 wt%). In this way, 2 and 20 wt% of SBS and SAN were added to H80/A20 and H20/A80 physical blends.

**Fig. 1** SEM micrograph (20,000 \times) of cryofractured surface of: **a** H80/A20 and **b** H20/A280

Results of mechanical behavior and blend morphology for each compatibilized blend are first discussed analyzing the influence of the kind of copolymer and then, for same compatibilizer concentration, a comparative performance evaluation was carried out. In all of cases corresponding physical blend is used as comparison parameter. Figure 2 present flexural mechanical performance for all blends prepared allowing to compare the influence of copolymer structure for different compatibilizer concentrations and relative amount of blend components.

Influence of the Kind of Compatibilizer

SBS presents typical rubbery behavior, with E and σ_u lower than base materials and physical blends (Table 2). Its molecules contain butadiene and styrene blocks. It is expected that these blocks act as compatibilizer because, both HIPS and ABS, contains the same molecules but in

different relative concentration. Then, compatibilization efficiency will depend on the relative amount of the initial copolymers in the blend. Results are discussed separately depending on the physical blend involved.

HIPS as Major Component

Figure 2a shows flexural mechanical properties of blends with major content of HIPS with 2 and 20 wt% of SBS compared with H80/A20. It is possible to note that when 2 wt% of SBS is incorporated to H80/A20, all mechanical properties decrease a few respect to the physical blend. This could be attributed to the low amount of SBS that possibly is not enough to reach the interphase, improve interfacial adhesion and then load transfer between phases. On the other hand, when 20 wt% of SBS is added, ϵ_b was improved reaching similar values to those of SBS and base materials. Also, E decreases while σ_u and toughness has

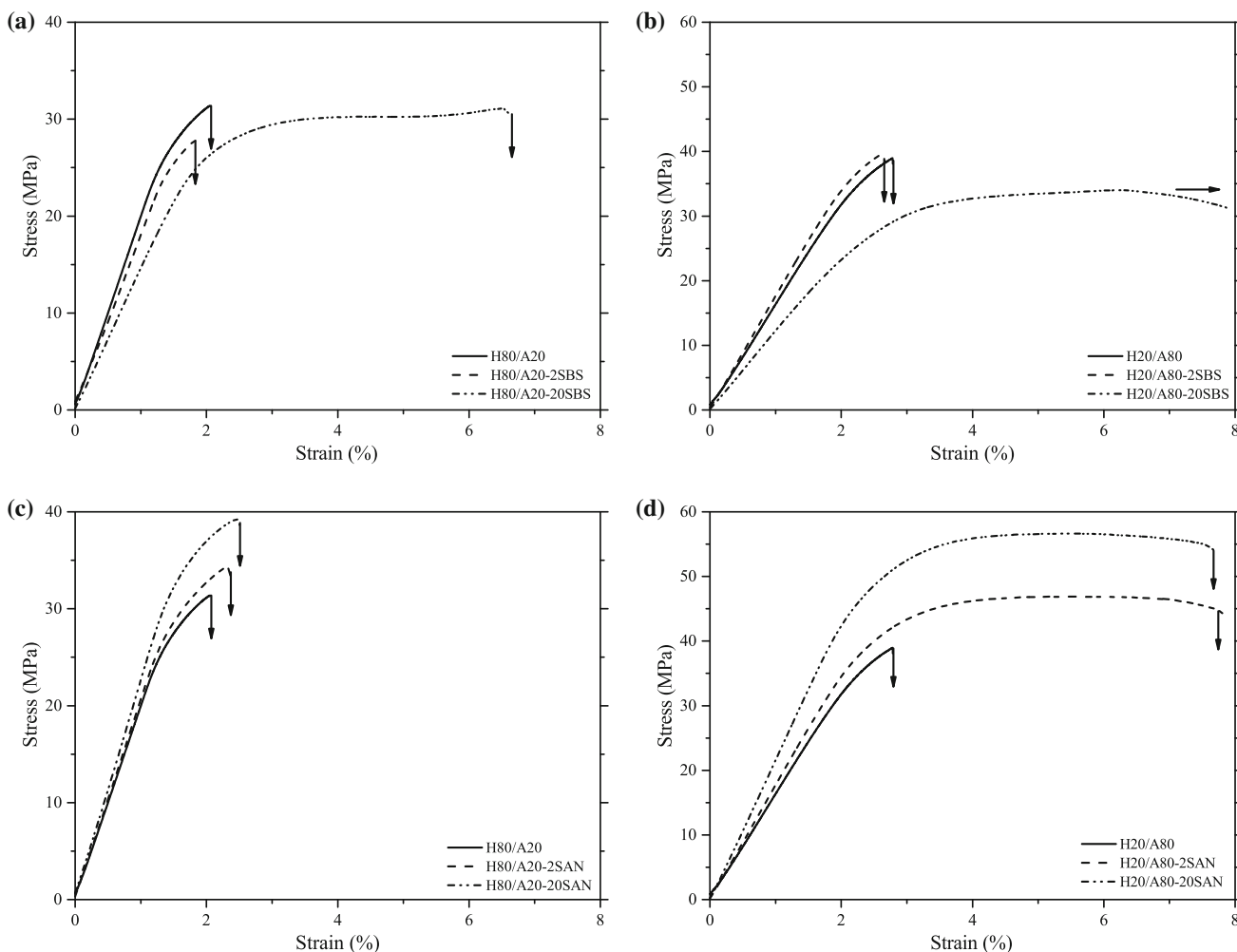


Fig. 2 Flexural stress–strain curves of physical and compatibilized blends: **a** major content of HIPS with 0, 2 and 20 wt% of SBS; **b** major content of ABS with 0, 2 and 20 wt% of SBS; **c** major

content of HIPS with 0, 2 and 20 wt% of SAN; **d** major content of ABS with 0, 2 and 20 wt% of SBS

been increased. These improvements indicate that SBS is acting as compatibilizer, improving phase distribution and adhesion because of the increase in elongation at break, toughness and strength. It is important to note that SBS could segregate in phases due to the high quantity added.

Micrographs of H80/A20 blends compatibilized with 2 and 20 wt% of SBS are shown in Fig. 3a, b. Blend with lower concentration of SBS presents a similar morphological structure to the corresponding physical blend H80/A20, but in the case of 20 wt% of SBS blend morphology is more rubbery with smaller domains, agreeing mechanical behavior. Besides compatibilization of physical blend H80/A20 with high concentration of SBS is evident, mechanical performance do not reach those of base materials. Also big quantity of a third copolymer to improve final properties is not economically viable, and then the addition of 20 % of SBS is not a feasible alternative for compatibilization of blends with major content of HIPS.

ABS as the Major Component

Flexural behavior of blends with ABS as the main component, with and without SBS, is shown in Fig. 2b. Blend with 2 wt% of SBS present a few decreases in the ϵ_b respect on H20/A80 physical blend. E and σ_u do not suffer

changes while toughness decrease. This behavior indicates that SBS is not acting as a compatibilizer due to mechanical properties related to phase adhesion and distribution has not been improved. On the other hand, with 20 wt% of SBS, E and σ_u decreases as it was expected due to the rubbery nature of the compatibilizer added, while toughness and ϵ_b are highly improved without break. Then, improvement in the adhesion between phases occurred but, because of the high amount of a rubbery material final blend has poor strength.

Figure 3c shows micrographs (20,000 \times) of H20/A80 blends with 2 wt% of SBS and Fig. 3d for 20 wt% of SBS. Morphology of blend with 2 wt% of SBS present more sharpen fracture edges than H20/A80 physical blend. Also, there is a reduction of phase domain, but less distribution of them. On the other hand, when 20 wt% of SBS is added, morphology exhibit rubbery surface with small size domains and wide distribution. This appreciations are consistent with flexural performance analyzes. Is important to note that, SBS does not act as a good compatibilizer for this physical blend, even toughness and ϵ_b have been improved the overall performance indicates that final material is more ductile than the bases.

The other compatibilizer used is SAN which is a stiff copolymer with high E and σ_u but poor ϵ_b . Its molecules

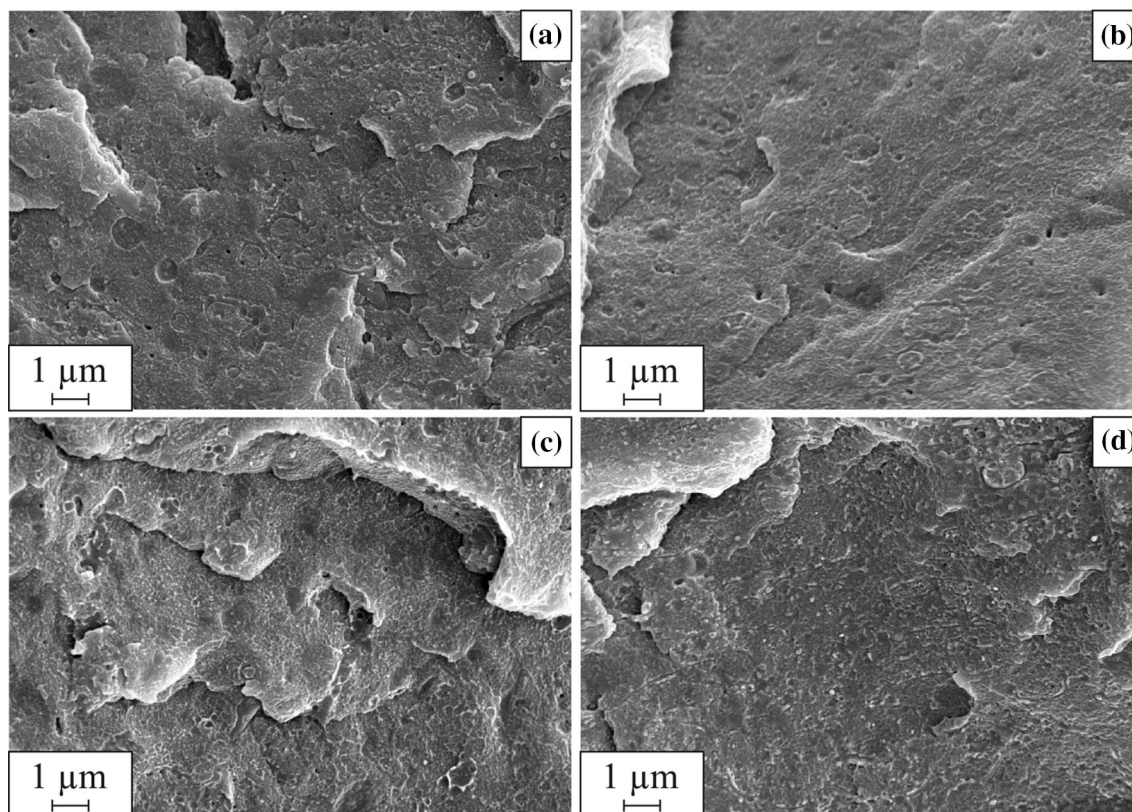


Fig. 3 SEM micrograph (20,000 \times) of cryofractured surface of: **a** H80/A20-2SBS; **b** H80/A20-20SBS; **c** H20/A80-2SBS and **d** H20/A80-20SBS

include styrene blocks, present in both base materials, and acrylonitrile blocks compatible with ABS. It is stiffer, more rigid and more fragile than base materials, then is possible to claim that interaction of its molecules with HIPS and ABS could compatibilize and also reinforce their blends. As it was mentioned above, for blends with SBS, compatibilization efficiency will depend on the relative amount of the initial copolymers in them. Again, results are discussed separately depending on the physical blend involved.

HIPS as Major Component

Figure 2c shows flexural mechanical behavior of H80/A20 with 2 and 20 wt% of SAN in comparison with the corresponding physical blend. When 2 wt% of SAN is added, flexural properties increase, but this increase is not as noticeable in ϵ_b , as in toughness, E and σ_u which indicates that SAN is acting just as a reinforcing agent, not as compatibilizer. Also when more SAN is added, 20 wt%, properties increase a few more than with 2 wt%, and again SAN is reinforcing physical blend with major content of HIPS. This behavior could be attributing to the low amount of ABS then SAN does not have necessary AN phase to interact and compatibilize.

In Fig. 4a, b are shown SEM micrographs for blend with major content of HIPS with 2 and 20 wt% of SAN respectively. Morphology of blend with 2 wt% SAN presents, respect to the corresponding physical blend, more sharpen edges with a stiff uniform surface and bigger domain sizes. These characteristics are more evident in the case of 20 wt% of SAN Blends morphology are consistent with flexural performance, showing fragile characteristics.

ABS as Major Component

Flexural mechanical properties for blends with major content of ABS with 2 and 20 wt% of SAN are shown in Fig. 2d. It is possible to note that blend with just 2 wt% of SAN improves notably its properties respect on the H20/A80 physical blend, reaching similar values to those of base materials. SAN compatibilization effectiveness is remarkable for this kind of blends. ϵ_b is improved 77 % with the only addition of 2 wt% of SAN, supporting the claim. The use of such low amount of compatibilizer is an important aspect for the economical point of view, then this compatibilization system present double advantages, good properties with low amount of compatibilizer added.

On the other hand, blend with 20 wt% of SAN has higher toughness, E and σ_u than blend with 2 wt% of

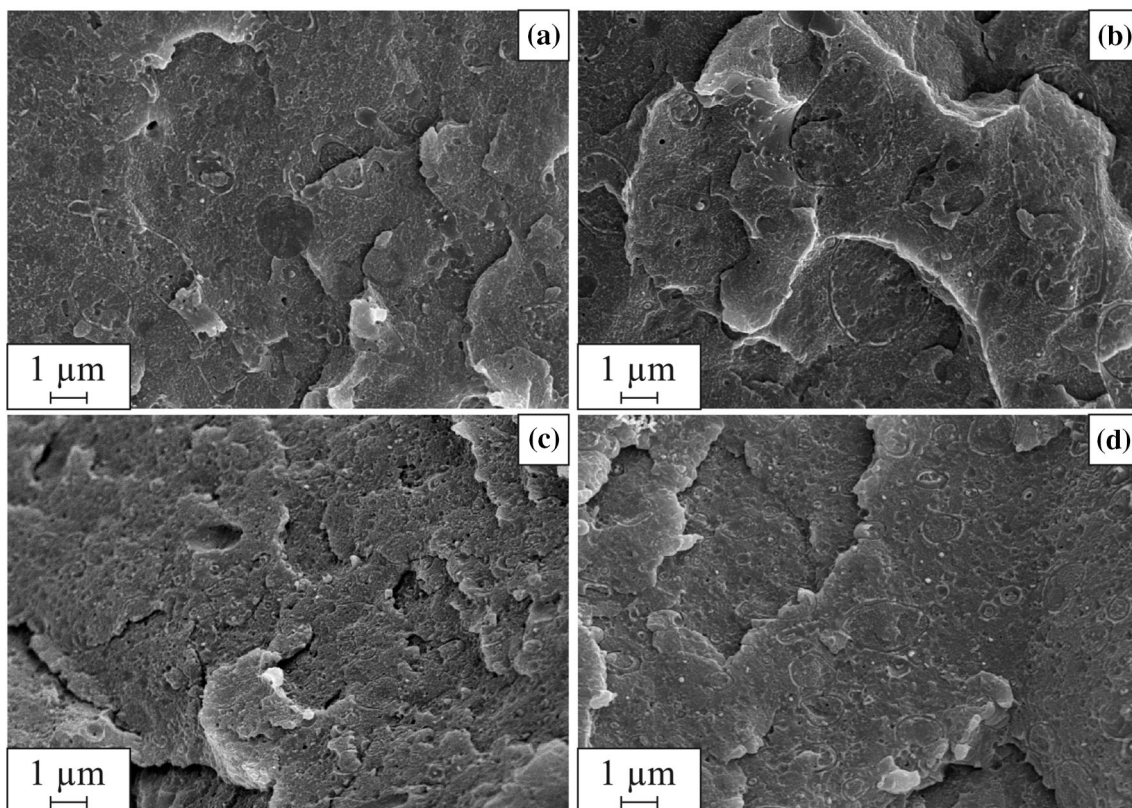


Fig. 4 SEM micrograph (20,000 \times) of cryofractured surface of: **a** H80/A20-2SAN; **b** H80/A20-20SAN; **c** H20/A80-2SAN; and **d** H20/A80-20SAN

compatibilizer, as expected, but the ϵ_b did not suffer considerable changes. Taking into account that ϵ_b increases approximately 80 % respect to the correspondent physical blend, it is clear that the improvement in phase adhesion respect to H20/A80 blend is lightly superior respect to blend with 2 wt% of SAN. This fact indicates that SAN molecules locates around interphases, but when it is saturated, SAN excess is incorporated as a phase reinforcing even more the physical blend. Please note that the incorporation of an amount 10 times bigger of compatibilizer allows a small enhancement in properties and increase notably costs, then it seems not economically viable.

Figure 4c, d shows cry-fracture surface SEM micrographs of blend with ABS as major component, with 2 and 20 wt% of SAN, respectively. Blend with 2 wt% of SAN present domain sizes smaller than de corresponding physical blend. Also, structure seems to have more rubbery behavior besides the addition of a stiffer material that indicates phase adhesion improvement. When the amount of SAN is bigger surface did not suffer much changes, but is possible to note an increment in size domain that could be attribute to a new phase of SAN. Both micrographs represent mechanical behavior of these blends, corroborating that SAN in low concentration results in a final blend with high flexural mechanical improvement.

Influence of the Amount of Compatibilizer

Figure 5 present flexural mechanical behavior for all blends prepared and reorganized in order to analyze the performance of the amount of compatibilizer on starting blends with major content of HIPS or ABS. Also, this figure allows making a comparison between the corresponding physical blend and both compatibilizer with the same concentration added. This approach lets analyze directly which kind and copolymer concentration use in order to improve mechanical performance of each physical blend.

HIPS as Major Component

Figure 5a show stress strain curves for blend with major content of HIPS with 2 wt% of SBS and 2 wt% of SAN compared with the corresponding physical blend (H80/A20). When 2 wt% of SBS is added to the blend, all properties deteriorate respect on the physical blend, indicating that compatibilization is not effective with this amount of compatibilizer, possibly by its segregation in a separate phase. On the other hand, for the same concentration but with SAN as a compatibilizer, all flexural properties have been improved. However, this increase is not enough to claim an effective compatibilization but, SAN is acting as a reinforcing agent, probably for a

combined effect some molecules reach interphases and other segregate acting as reinforced agent. However, the compatibilization effect is low as the ABS is the minor phase. For H80/A20 physical blend, it is possible to say that the addition of low amounts of SBS or SAN does not act as a good compatibilizer, because a high strain property has not been improved.

Flexural behavior of blends with 20 wt% of SBS and 20 wt% of SAN in comparison with the major content of HIPS physical blend (H80/A20) is shown in Fig. 5b. The addition of 20 wt% of SBS increases notably toughness and ϵ_b , but E suffer a deterioration that can attribute to the high amount of SBS which is a material with very rubbery behavior. However, besides the considerable amount of rubber added, σ_u conserve its value respect on the physical blend. This last point in addition with the improvement in toughness and elongation indicates clear enhancing in phase adhesion. On the other hand 20 wt% of SAN increase all flexural properties respect on H80/A20. However, the increasing in ϵ_b is not notable higher. Regarding mechanical performance of blend with high amount of SAN is possible to conclude that in this case, the compatibilizer is acting as a reinforcing agent and phase segregation has increase notably. Then, for high concentration, SBS has the best performance, and the compatibilization is effective, but 20 wt% of a third virgin copolymer is not economically viable.

ABS as Major Component

Blends with major content of ABS mechanical behavior with 2 wt% of SBS and 2 wt% of SAN in comparison with the physical blend (H20/A80) are shown in Fig. 5c. It can be appreciate that when 2 wt% of SBS is added to this physical blend toughness and ϵ_b decrease while the other properties do not suffer changes. On the other hand, when 2 wt% of SAN is added, all properties increase respect on the physical blend H20/A80, particularly ϵ_b . These results indicates, as it was mention above, that SBS in low concentration do not act as a compatibilizer, while SAN performance indicates that phase adhesion has been improved and then this copolymer compatibilization is effective.

Mechanical performance of ABS major content blends, compatibilized with 20 wt% of SBS and 20 wt% of SAN in comparison with the corresponding physical blend, H20/A80, is shown in Fig. 5d. A 20 wt% of SBS increases toughness in 200 %, while E and σ_u , decrease in 30 and 18 % respectively, without breaking. On the other hand, when 20 wt% of SAN is added, all properties increase notably, around of 75 %, on average. Then, it is possible to conclude that, SBS improves phase adhesion mainly due to its rubbery behavior, becoming blends more ductile. SAN is the opposite case because all properties increase, but the

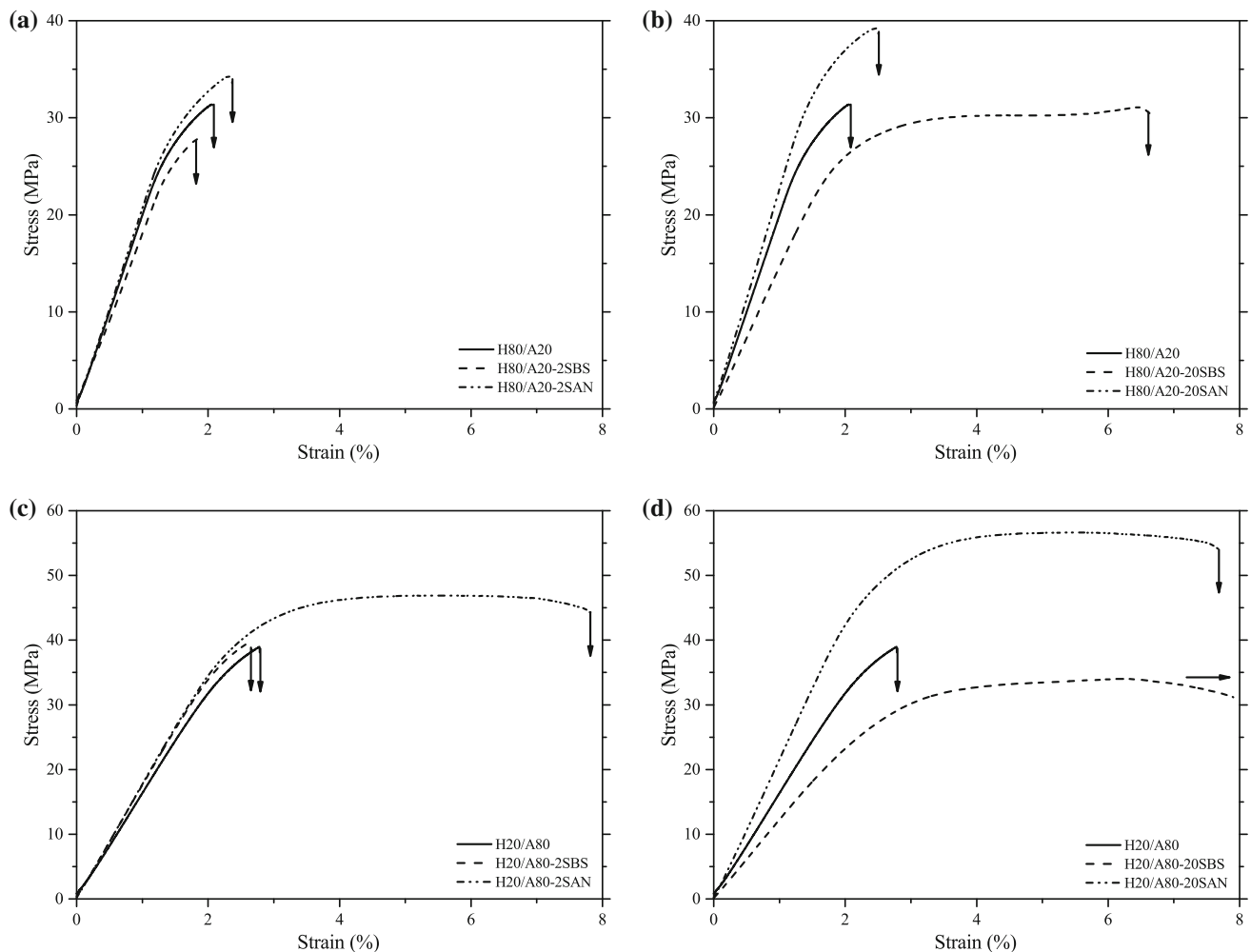


Fig. 5 Flexural stress–strain curves of physical and compatibilized blends: **a** major content of HIPS with 0 wt% of compatibilizer, 2 wt% of SBS and 2 wt% SAN; **b** major content of HIPS with 0 wt% of compatibilizer, 20 wt% of SBS and 20 wt% SAN; **c** major content of

ABS with 0 wt% of compatibilizer, 2 wt% of SBS and 2 wt% SAN; **d** major content of ABS with 0 wt% of compatibilizer, 20 wt% of SBS and 20 wt% SAN

high increase of σ_u even more than base materials is suggesting that SAN not only acts as a compatibilizer but also as a reinforcing agent. However, such high amount of a copolymer as a compatibilizer is not a viable option from the economical point of view.

Conclusions

From the study of direct mixing of HIPS and ABS is possible to remark that final blends obtained are not self-compatibilizer independently of the proportion of HIPS/ABS used. Flexural mechanical properties of the resulting blends are poorer than base materials.

From the compatibilization screening study presented, it is possible to conclude that in blends with major content of HIPS, SBS seems to be better than SAN to compatibilize

the corresponding physical blend, but the overall mechanical performance was not improved by the big amount of a rubbery compatibilizer. On the other hand, SAN acts as a reinforcing agent in both concentration used, improving mechanical resistance.

In the case of blends with ABS as major component, SBS only is effective as a compatibilizer when is added in high amount, improving toughness and elongation but losing strength and stiffness because of its rubbery character. On the other hand, SAN results a good compatibilizer in small quantities. Only 2 wt% of SAN increase toughness in a 350 %, elongation in a 77 %, mechanical resistance in a 17 % and modulus in a 10 %, indicating a remarkable improvement of phase adhesion. High amount of SAN shows that the excess in the compatibilizer incorporated is compatibilizing but also acting as a reinforcing agent. However, the addition of 20 wt% of SAN

produce small enhancements in mechanical properties in comparison to the addition of 2 wt% of SAN, then is not economically viable because of the notably costs increase.

The study made in this work allows assessing compatibilizer concentrations range for future work in cases where SBS is used. Apparently, it is expected that that major content of ABS blends with SBS concentrations between 2 and 20 wt% could give final materials with good mechanical performance. Also, in HIPS as major content blends is necessary to find the amount of compatibilizer to increase phase adhesion and then make effective the compatibilization.

The present work is a progress in compatibilization studies of this kind of complex blends. To find methodologies economically viable and process friendly is a fundamental step in the recycling of this very important electrical and electronic plastic waste, mainly composed by HIPS and ABS.

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References

- European Union 2003b (2003) Directive 2002/96/EC of the European Parliament and of the council of 27 January 2003 on waste electrical and electronic equipment (WEEE). Off J Eur Union L 37:24–38
- Namias J (2013) The future of electronic waste recycling in the United States: obstacles and domestic solutions. Department of Earth and Environmental Engineering, Columbia University, New York
- Statista (2016) Disposal of used mobile phones. <http://www.statista.com/statistics/270793/disposal-of-used-mobile-phones/>. Accessed 7 June 2016
- Baxter J, Wahlstrom M, Castell-Rüdenhausen MZ, Frane A, Stare M, Løkke S, Pizzo M (2014) Plastic value chains—Case: WEEE (Waste Electric and electronic equipment) in the Nordic region. Nordic Council of Ministers. TemaNord, Denmark
- Goodship V, Stevels A (2012) Waste electrical and electronic equipment (WEEE) handbook. Woodhead, USA
- An J, Kim C, Choi BH, Lee JM (2014) Characterization of acrylonitrile–butadiene–styrene (ABS) copolymer blends with foreign polymers using fracture mechanism maps. *Polym Eng Sci* 54:2791–2798
- Cafiero L, Fabbri D, Trinca E, Tuffi R, Vecchio Cipriotti S (2015) Thermal and spectroscopic (TG/DSC–FTIR) characterization of mixed plastics for materials and energy recovery under pyrolytic conditions. *J Therm Anal Calorim* 121:1111–1119
- Wu S (1982) Polymer interfaces and adhesion. Marcel Dekker, New York
- Utracki LA (1989) Polymer alloys and blends. Hanser, Munich
- Elmendorf JJ, Vander Vegt AK (1991) Phase polymer systems. Hanser, Munich
- Bisio AL, Xanthos M (1995) How to manage plastics wastes: technology and market opportunities. Hanser, New York
- Utracki LA (2013) Commercial polymer blends. Springer, Berlin
- Milner S, Xi H (1996) How copolymers promote mixing of immiscible homopolymers. *J Rheol* 40:663–687
- Favis BD (2000) Polymer blends. Wiley, New York
- Bucknall CB, Frederic FP, Cote FFP, Partridge IK (1986) Effects of rubber particle volume fraction on deformation and fracture in HIPS. *J Mater Sci* 21:301–306
- Hoyle W, Karsa DR (1997) Chemical aspects of plastics recycling. American Chemical Society, USA
- Scaffaro R, Botta L, Di Benedetto G (2012) Physical properties of virgin-recycled ABS blends: effect of post-consumer content and of reprocessing cycles. *Eur Polym J* 48:637–648
- Yamaguchi M (2015) Mechanical properties and structure of rubber-toughened immiscible blends. In: Müllen K, Kobayashi S (eds) Encyclopedia of polymeric nanomaterials. Springer, Berlin, pp 1214–1218
- Arnold JC, Watson T, Alston S, Carnie M, Glover C (2010) The use of FTIR mapping to assess phase distribution in mixed and recycled WEEE plastics. *Polym Test* 29:459–470
- Datta S, Lohse DJ (1996) Polymeric compatibilizers. Hanser, Munich
- Brandrup J, Bittner M, Michaeli W, Menges G (1998) Recycling and recovery of plastics. Hanser, Munich
- Utracki LA (2002) Compatibilization of polymer blends. *Can J Chem Eng* 80:1008–1016
- Peydro Rasero MÁ, Juárez Varón D, Sánchez Caballero S, Parres F (2013) Study of the mechanical properties of acrylonitrile butadiene styrene-high impact polystyrene blends with styrene ethylene butylene styrene. *Ann Univ Oradea* 22:269–272
- Nielsen L, Landel R (1994) Mechanical properties of polymers and composites. Dekker, USA