On a contribution to study some mechanical properties of WEEE recycled polymer blends

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Abstract

This research deals with the study of acrylonitrile-butadiene-styrene/polycarbonate (ABS/PC) totally derived from wastes of electrical and electronic equipment (WEEE). The aim of this study is to investigate the macroscopic use properties of 100% recycled polymers and compare them with the virgin materials. First, a preliminary work of sorting and characterization of the wastes was necessary to identify the predominant polymer components in the lots. Then, four compositions of blends (ABS/PC) were performed at laboratory using the twin-screw extruder and injection techniques. Next, a series of experimental tests were carried out to investigate the morphology of the blends, their mechanical and thermo-mechanical behavior. The experimental results highlighted the synergistic effect by blending ABS and PC wastes. In addition, the comparison with the virgin mixtures has shown a decrease in the mechanical properties of the waste blends, however, the mechanical behavior is still ductile and the blends stiffness was enhanced.

KEYWORDS

ageing, glass transition, mechanical properties, recycling, thermoplastics

1 | INTRODUCTION

Over the past decade, concerns have been raised in front of the increasing waste derived from electrical and electronic equipment labeled wastes of electrical and electronic equipment (WEEE).[1,2] The latter refers to the end-of-life of electrical or electronical equipment like phones, TV screens, computers, household appliances, and so forth. WEEE are composed with 20% on average of plastic materials, which represents a deposit of more than 78,000 tonnes of plastics in France in 2014.[3] More general, the generation of WEEE has tremendously increased all over the world leading to 53.6 Mt of waste in 2019.[4] Accordingly, the management of WEEE is positioned, nowadays, as a crucial key in the framework of the strategies put in place for the plastics waste control. Apart from their superabundance, the developed strategies can be explained by the nature itself of WEEE considered partially dangerous (content of heavy metals, polychlorinated biphenyls, brominated flame retardants, additives and other hazardous materials),[5] but also because they can contain precious materials such as copper and rare metals.[6] On this basis, WEEE are considered as potential sources of attractive materials which can respond to the problematic of the depletion of natural resources. Accordingly, the recycling alternative appears very interesting in order to upgrade these materials and to make them beneficial for the industrials needs.[7]

In this context, this research is involved under the framework of a larger study dealing with the compatibility of polymers blends derived from WEEE. A part of this research, particularly dedicated to the miscibility of polymer blends under different processing methods, was previously published by the authors.[8] This study is an attempt to investigate the macroscopic end properties of acrylonitrile-butadiene-styrene/polycarbonate (ABS/PC) blends totally derived from the end-of-life equipment. The ABS/PC system is one of the well-known engineering plastics widely used in several industrial applications notably in automotive sector. This combination finds its success thanks to the synergistic performances obtained by blending two different amorphous homopolymers: the ABS and the PC. The former, a rubber polymer, is particularly advantageous for its good processability, its low cost and notch impact resistance, whereas the latter, a hard plastic one, is known for its excellent mechanical and thermal properties.[9,10] The ABS polymer is made of three different monomers: the acrylonitrile contributing to its chemical resistance and heat stability, the butadiene offering toughness and impact strength and the styrene providing rigidity and processability. Thanks to this rich chemical composition, the ABS terpolymer can find uses in a versatile range of industrial applications such as automotive as a substitute to heavy metal parts, pipes and fitting, appliances, electric and electronic applications, etc.[11] On the other hand, the polycarbonate is known for its heat resistance and high strength making it resistant to impact and fracture. Added to its lightweight and transmittance properties, the polycarbonate is very useful for industrial applications requiring high performances, like medical, automotive and transportation, building and construction, amd so forth.[12]

Although the difference in both polymers' properties, the ABS and PC have shown to exhibit a good compatibilization when blended together as well as promising properties.

For theses reasons, many researches have focused on the study of virgin ABS/PC blends.[13,14] Guinault et al.,[15] for instance, have studied the thermomechanical properties of virgin ABS/PC blends obtained by an original coextrusion method (CM) and concluded that the technique has little effect on the yield stress but enhanced significantly the elongation at break of the blend. Krache et al. have investigated the effect of the polycarbonate addition on some mechanical and thermal properties of ABS/PC blends and it was noticed an improvement of the mechanical ultimate properties (impact strength and toughness) of the blends.[16] Although the extensive works reported in literature about the ABS/PC blends, a few researches dealt with real recycled ABS/PC systems derived from WEEE and still, further information on WEEE plastics is needed for a better understanding of their behavior and thereby upgrading of these materials.[17]

In the present research, we focused on a 100% recycled ABS/PC blends derived from WEEE supplied by Ecosystem company and collected from different waste sites in France. The characterization of the different lots of wastes is described to allow the identification of the predominant polymers in the lots. Based on these first results, several compositions of ABS/PC blends were performed and their ultimate mechanical performances were experimentally investigated.

2 | EXPERIMENTAL

This section is devoted to the description of the experimental part of this research related to the characterization of the supplied WEEE in order to identify their composition in terms of polymer matrices. This first investigation is a compulsory step for the recycling process enabling the knowledge of the predominant polymers in the waste lots for their recovery.

2.1 | Characterization of WEEE: Polymers and additives identification

Three batches of plastic wastes of EEE were collected by Ecosystem company from four different waste sites in France and supplied for investigation in order to promote quality control and recycling of plastic waste. The WEEE lots used of this study consist of a mixture of flat screens, cathode-ray tube screens (CRT) and small household appliances screens (PAM). First of all, a preliminary step of waste sorting and sampling (Figure 1) was performed at the research laboratory of ENSAM (Chambéry-France) according to the normalized specifications TS 50625–3-1.

Then, an analysis by medium infrared spectrometry MIR was carried out on the samples derived from the sampling operation. Finally, and for reasons of traceability, the samples were subjected to a complementary physicochemical characterization by TGA and DSC in order to check and validate the first results obtained by MIR, especially for the materials with a styrene matrix which have a very close chemical signature.

The identification results of the polymer components contained in WEEE Flat screens, CRT and PAM screens are summarized in Figure 2.

FIGURE 1 Wastes of electrical and electronic equipment (WEEE) sampling [Color figure can be viewed at wileyonlinelibrary.com]

It can be noticed from the thermal analysis of WEEE samples that the components are mainly thermoplastics and that there is a predominance styrene compounds like HIPS, ABS and PC-ABS. The main additives present in WEEE are brominated flame retardants (BFRs) like tetrabromobisphenol A, Decabromodiphenyl ether and hexabromocyclododecane. Note that the characterization of these additives is not in the scope of the present study.

Based on these results, it was decided to consider the composite ABS/PC for the following study. Apart from its predominance in the three WEEE lots, this choice was also motivated by the industrial interest of this engineering thermoplastic which has gained a great importance thanks to the wide range of applications it finds use like automotive, electronics and telecommunication, medical and pharmaceutical devices, etc.[18,19]

2.2 | Materials description

The PC and the ABS derived from the WEEE are used for the blend preparation of ABS/PC. This blend system is very interesting in that it includes an homopolymer, the PC known for its high toughness, and a terpolymer, the ABS for which inclusions of polybutadiene are dispersed in the copolymer styrene matrix (SAN) known for its good properties of flexibility and shock resistance. This alliance between these different polymer natures can lead to a performance synergy for the blend ABS/PC.

First, ABS and PC polymers were characterized and their physical properties are given as follow:

The density for ABS polymer was 1040 kg/m^3, Vicat Softening Temperature (VST B): 96°C and Melt Volume Rate (MVR): 19 cm^3/10 min.

In the case of the polycarbonate, the density was 1020 kg/m^3, VST B: 140°C and MVR: 21 cm^3/10 min.

2.3 | Blends processing

2.3.1 | Extrusion of blends

Blends from ABS and PC wastes were performed by extrusion and injection methods. First, since the materials are humidity sensitive, they were dried before

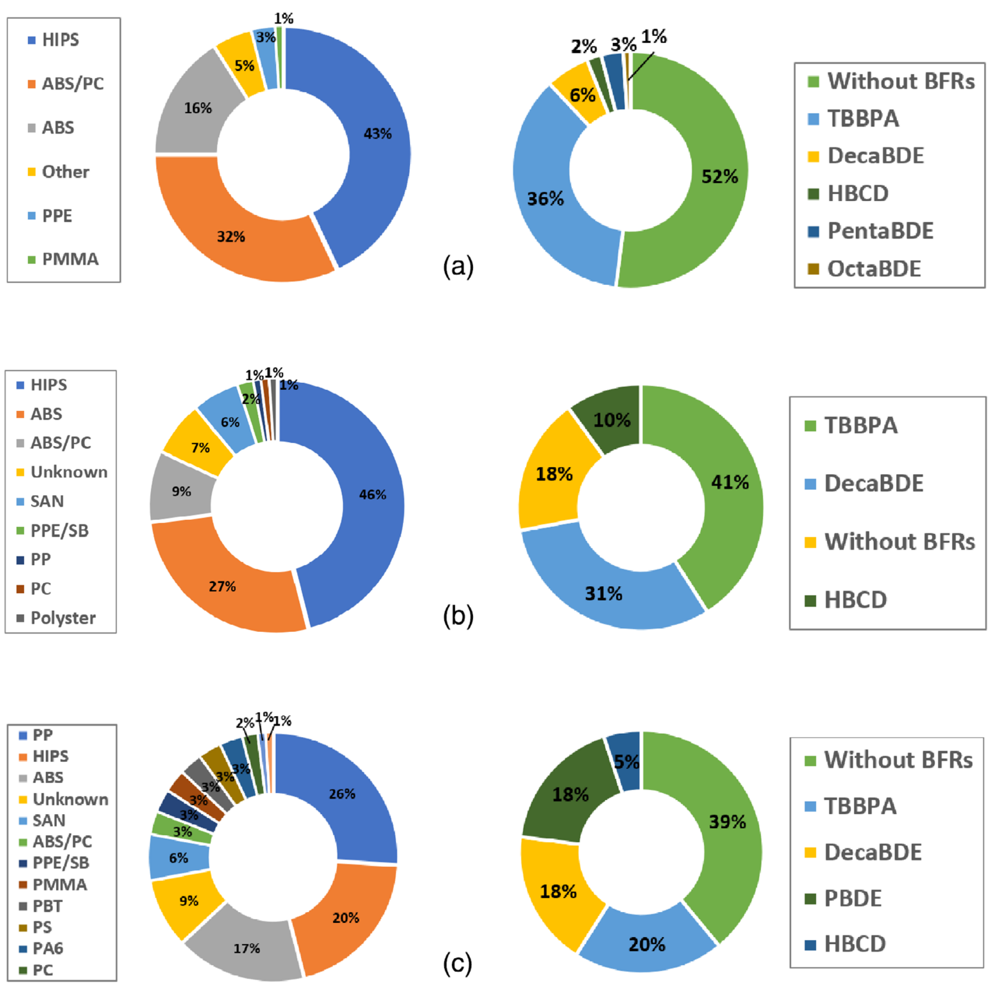


FIGURE 2 Results of wastes of electrical and electronic equipment (WEEE) identification; polymer matrices (on the left) and additives (on the right), (a) flat screens, (b) cathode-ray tube (CRT) screens, (c) small household appliances (PAM) screens [Color figure can be viewed at wileyonlinelibrary.com]

processing using an oven EP ENGIN PLAST DUE. The drying conditions are summarized in Table 1.

Next, ABS and PC in pellets form were extraduated using a co-rotating twin-screw extruder (TSE) with interpenetrating and intermeshing screws from Thermo Haake (PTW 16-40D model). In total, four compositions were considered: ABS/PC (0/100), ABS/PC (30/70), ABS/PC (70/30) and ABS/PC (100/0). For each composition, the appropriate parameters for the extrusion, such as the temperature of the heating zones, flow rate and screw rotation speed were defined. In fact, the extrusion of the different ABS/PC blends was carried out at different temperatures adjusted according to the type of the major polymer in each mixture and taking into account the temperatures of both processing and degradation of each polymer. Tables 2 and 3 summarize the extrusion parameters used for the blends.

It can be noticed from Table 2 that the setpoint temperatures tend to decrease throughout the barrel to the die when the PC is the major component in the blend in order to avoid the overheating and the degradation of ABS. In contrast, when ABS is predominant (Table 3), the temperatures are around 185°C and gradually increase along the barrel to 215°C for the last heating zones. This increase is intended to facilitate the extrusion and the exit of ABS.

The last step of the extrusion consists on the recovery of the polymer blend. Indeed, after the exit of the screw from the polymer mixture, it passes through a cylindrical die, which allows to extrude a profile with an average diameter of around 4 mm. Rushes extrudates pass through a water tank located at the outlet of the extruder and are continuously cut using a granulator to obtain the granules to be used for the injection process.

2.3.2 | Injection of blends

The granules of the two mixtures resulting from the TSE are dried at 80°C. The material is then injected using a computer-controlled injection molding machine (model DK CODIM 175/410). The obtained injected specimens are of type A1 with dimensions specified according the ISO527-2, 1996.

In addition, virgin four blends of ABS/PC of the same compositions than the waste blends were prepared in laboratory and will be used for reference. The blends were composed of commercial ABS (GP 22) and PC (121R) polymers from Gazechim Plastics (France). It shall be noted that the extrusion and the injection operations of the virgin blends were performed using the same procedure than the aforementioned one.

TABLE 1 Drying conditions of waste polymers

	ABS	PC
Drying temperature (°C)	80	120
Drying time (hour)	48	48

Abbreviations: ABS, acrylonitrile-butadiene-styrene; PC, polycarbonate.

2.4 | Morphology observation

Morphological observations of the different blends were performed by scanning electron microscopy (SEM), model MEB HITACHI 4800. Because of the insulating aspect of polymer materials, all samples were coated with a thin gold layer of about 50 Å of thickness before being observed.

The SEM observations of ABS/PC blends were performed on two kinds of surfaces:

- Fractured surfaces derived from tensile tests performed on ABS/PC specimens. These observations allow to observe the fracture surface as well as the morphology and the adhesion quality between the different phases of the mixture.
- Surfaces of polymer films produced by selective dissolution in acetone solvent and then recovered after drying. The purpose of the selective dissolution is to eliminate just one phase (a polymer) in the mixture. Unlike the PC polymer, ABS can readily dissolve in acetone.

2.5 | Analysis by dynamical mechanical thermal analysis

Dynamic mechanical thermal analysis (DMTA) was used to investigate the thermomechanical properties of ABS/PC blends. In particular, we focused on the evolution of the viscous (loss) modulus as a function of the temperature. The curve peak enables to determine the glass transition of materials. The tests were carried out using a Q800 device from TA instrument (France) with a frequency equal to 1 Hz and a heating rate of 2°C/min in the range of temperature − 20 to 180°C. For the injected samples (type A1 specimens), three-point bending tests were performed. The samples have a total length of 75 mm, a width of 12.75 mm and a thickness of 2 mm.

2.6 | Uniaxial tensile test

Uniaxial tensile tests were performed on A1 injected specimens of ABS/PC blends. Mechanical properties such as the Young's modulus, the yield stress, the break

TABLE 2 Extrusion parameters for the blend ABS/PC (30/70)

Heating zone	1	2	3	4	5	6
T (°C)	270	270	240	240	240	240
Screw rotation speed (rpm)	300					
Flow rate (rpm)	25					

TABLE 3 Extrusion parameters for the blend ABS/PC (70/30)

Heating zone	1	2	3	4	5	6
T (°C)	185	190	200	210	215	215
Screw rotation speed (rpm)	300					
Flow rate (rpm)	17					

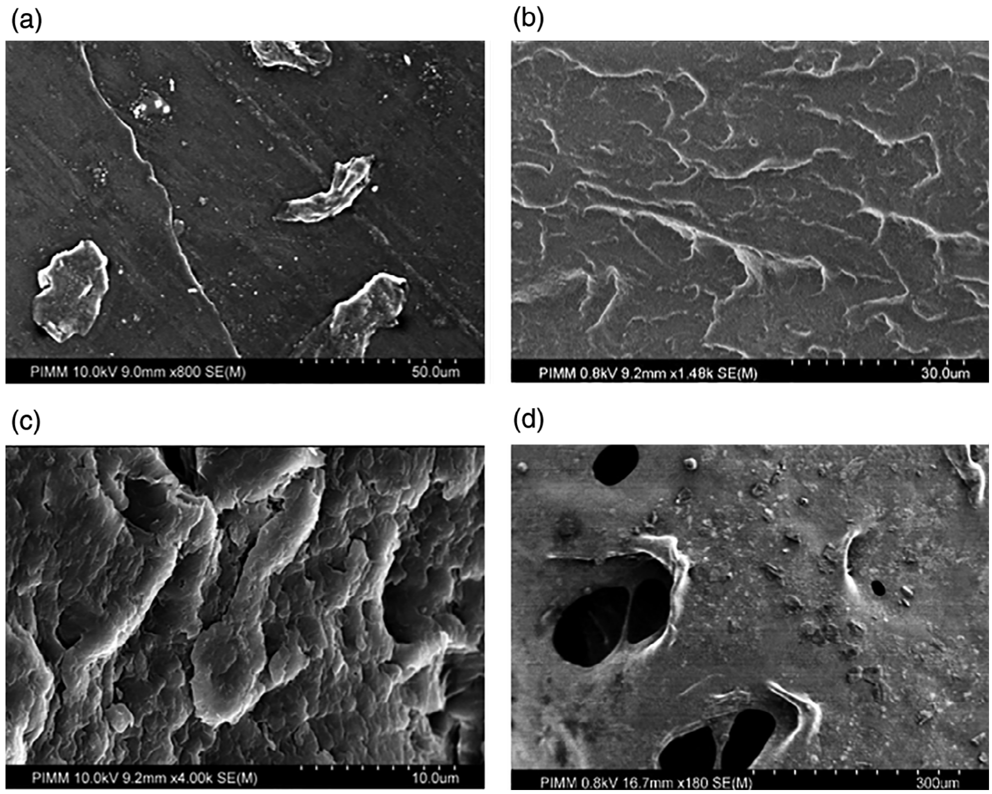


FIGURE 3 Micrographs of scanning electron microscopy (SEM) observations of wastes of electrical and electronic equipment (WEEE) acrylonitrile-butadiene-styrene/polycarbonate (ABS/PC) blends: (a) ABS/PC (100/0) fractured surface, (b) ABS/PC (70/30) fractured surface, (c) ABS/PC (30/70) fractured surface, (d) ABS/PC (30/70) after dissolution in acetone

elongation and the break stress were measured by a universal tensile machine (Instron model 4507). The measurements were performed at laboratory room temperature with a crosshead speed of 3 mm/min.

3 | RESULTS AND DISCUSSION

3.1 | SEM observation

The microstructures of the waste injected blends of ABS/PC observed by SEM are depicted in Figure 3. As mentioned earlier, two kinds of surfaces were considered to perform the morphological observations: the fracture surface by tensile test and the surface obtained by selective dissolution in acetone solvent. It can be noticed from Figure 3a the microstructure of ABS/PC (100/0) which reveals the presence of some inclusions of polybutadiene dispersed in a continuous matrix which represents the SAN elastomeric phase.[17] One can also observe a continuous oblique line across the image which could be probably attributed to the damage phenomenon of the specimen due to its fracture by the mechanical tensile test.

Figure 3b,c shows the morphology of the fracture surfaces of the blends ABS/PC (30/70) and (70/30), respectively. The micrographs exhibit a rather fibrillar tendency

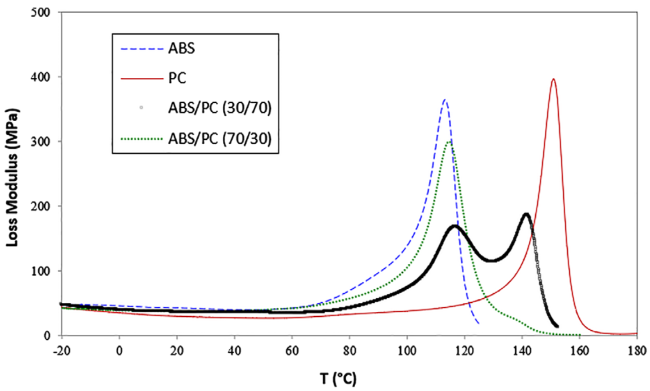


FIGURE 4 Loss modulus evolution of the waste blends acrylonitrile-butadiene-styrene/polycarbonate (ABS/PC) obtained by dynamic mechanical thermal analysis (DMTA) [Color figure can be viewed at wileyonlinelibrary.com]

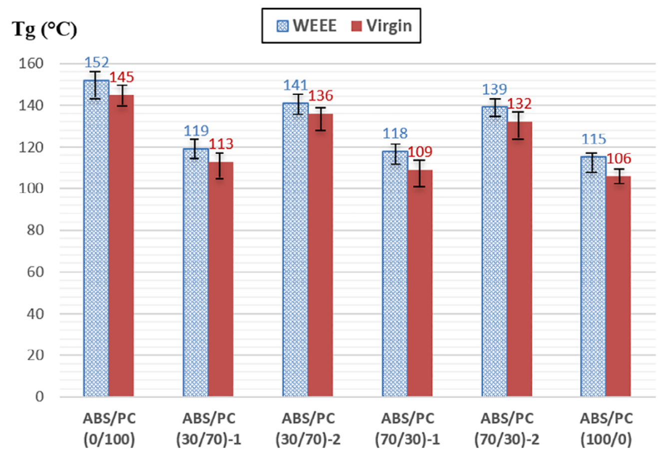


FIGURE 5 Comparison of glass transition temperatures of wastes of electrical and electronic equipment (WEEE) recycled blends versus virgin blends [Color figure can be viewed at wileyonlinelibrary.com]

oriented according to the direction of crack propagation. Also, it shall be pointed out that it is quietly hard to distinguish the ABS from the PC phase in these micrographs which can be synonym of the good adhesion between the two phases into the blends. Note that the TSE process was also favorable to ensure a good mixing between the polymers and thus a homogeneous aspect.

Nevertheless, by dissolving the ABS in the solvent (which is not a solvent for the PC polymer), the SEM observations of ABS/PC films can easily reveal the presence of inclusions of ABS dispersed in the PC matrix (Figure 3d). The inclusions of ABS are shown in the last micrograph as dark holes in the polycarbonate matrix, of nearly spherical shape with a diameter ranging from 10 to 90 μm.

3.2 | DMTA results

Figure 4 presents the evolution of the loss modulus with temperature for all the compositions of ABS/PC blends derived from WEEE. The analyze of the curves peaks shows that the transition of the waste PC is about 152°C, whereas the ABS shows a transition at 115°C. Normally, the ABS polymer exhibits two transitions at low and high temperatures corresponding to the transitions of the butadiene and SAN phases, respectively. The first glass transition occurs at approximately −82°C, and therefore can not be shown in the considered temperature range − 20 to 180°C.

By mixing the ABS and PC waste polymers, two glass temperatures can be detected for the blends (30/70) and (70/30) relative to the ABS and PC homopolymers presence. This finding is a relatively classic result in literature notably for virgin blends and can be often ascribed to a certain chemical affinity between the ABS and the PC.[20,21] More recently, in a previous research of the authors, it was demonstrated that the shift of the glass transition temperatures is due to the partial miscibility of the ABS and the PC polymers in the blends obtained by the extrusion process.[8]

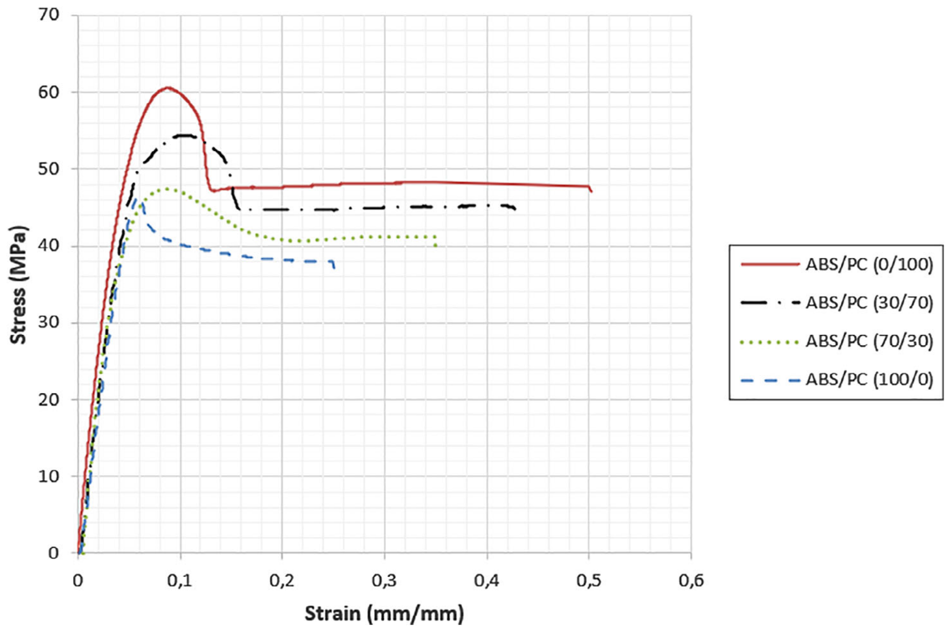
Besides, it can be noticed a decrease in the peak curves of the blend, notably for the ABS/PC (30/70) for which the intensity of the loss modulus drops significantly. This confirms the energy absorption ability due to the creation of chemical polymer interactions in the blend.

Regards the glass transitions temperatures, it was recorded transitions at 119 and 141°C for the ABS/PC (30/70) versus 118 and 139°C for the ABS/PC (70/30). One can note that when the PC is predominant in the blend, the glass transition of the mixture tends to shift towards that of the polycarbonate. By contrast, when the ABS is the major component in the blend, the glass transition of the latter tends to approach to that of the ABS.

On the other hand, the glass transition temperatures of virgin blends were measured and results are summarized in Figure 5. It can be observed in the light of this histogram that the glass transition temperatures of WEEE blends increase slightly in comparison with the virgin blends. Note that the intermediate compositions of ABS/PC blends (30/70) and (70/30) exhibit two glass transitions referenced herein as "-1" and "-2" in the figure, relative to the coexistence of both polymers ABS and PC in the mixture.

The increase of the glass transition can be attributed to the aging phenomenon of the amorphous waste polymers. This aging, added to the melting by recycling process could have implied a transformation in the

FIGURE 6 Stress–strain evolution of wastes of electrical and electronic equipment (WEEE) acrylonitrile-butadiene-styrene/polycarbonate (ABS/PC) blends during tensile test [Color figure can be viewed at wileyonlinelibrary.com]



microstructure of the materials leading, thereby to more hardened polymers. Moreover, since the considered polymers are amorphous, the molecular chains would be subjected to more entanglement due to the mechanical solicitation during the processing. This entanglement would prohibit the free mobility between the polymer chains and made the material stiffer. Besides, one can not exclude the possibility of crosslinking reaction during the blending of the two polymers and the formation of backbones which could have locked much more the freedom degree of chains. As a consequence, the transition from the rigid glassy state to the soft rubber one could be delayed as the rigidity of the polymer chains increased, implying thus an increase in the glass transition temperature for the aged polymer blends.[22]

3.3 | Mechanical tensile behavior

The A1 injected specimens of ABS/PC blends were subjected to the mechanical tensile test until fracture at ambient temperature. It shall be noted that for each composition of ABS/PC blends, tensile tests were performed on at least 10 specimens by following the same experimental protocol, and the average results are presented here.

The results of the stress–strain behavior of different WEEE blends are reported in Figure 6. In general, it can be noticed that the different curves exhibit approximately a reproductible tendency except obviously at the fracture level as it is a phenomenon initiated by a defect in the specimen and therefore not reproducible by nature. A ductile behavior of the waste ABS/PC can be observed for all the compositions unlike most incompatible mixtures. In particular, it can be seen that the tendency of the ABS curve (ABS/PC 100/0, bottom curve) is characteristic of that of amorphous polymers loaded with butadiene, with a “softening” zone after the elastic one, corresponding to the matrix damage by the formation of microstructural defects during stretching. Finally, the failure of the specimen occurs at strains around 25%.

On the contrary, the stress–strain evolution of WEEE polycarbonate (ABS/PC 0/100, upper curve) is slightly different since it highlights the formation of a necking phenomenon (with the drop of the associated nominal stress) after the elastic zone, followed by a “cold-drawing” plateau corresponding to the necking propagation along the specimen. The failure occurs at around 50% of the strain. These findings underline clearly the ductility of the PC polymer in comparison with the ABS one. Furthermore, one can see that the PC curve exhibits the highest values of the yield strength as well as the stress and the elongation at break.

By the addition of the ABS polymer to the polycarbonate, one can notice a slight change in the curves of the intermediate blends (ABS/PC 30/70 and 70/30), well situated within the spectrum between the homopolymers curves. The change is more pronounced with the addition of ABS as the peak widens, its intensity drops and the behavior becomes more and more brittle, so that the failure occurs not far the yielding. This denotes a loss of ductility in the mechanical behavior of the blend by the addition of the ABS polymer. In fact, the capacity of the polycarbonate to undergo higher strains with the neck propagation is hampered by the presence of the rubber ABS in the blend. These results corroborate the findings of Greco et al. obtained with virgin ABS and PC polymers.[23]

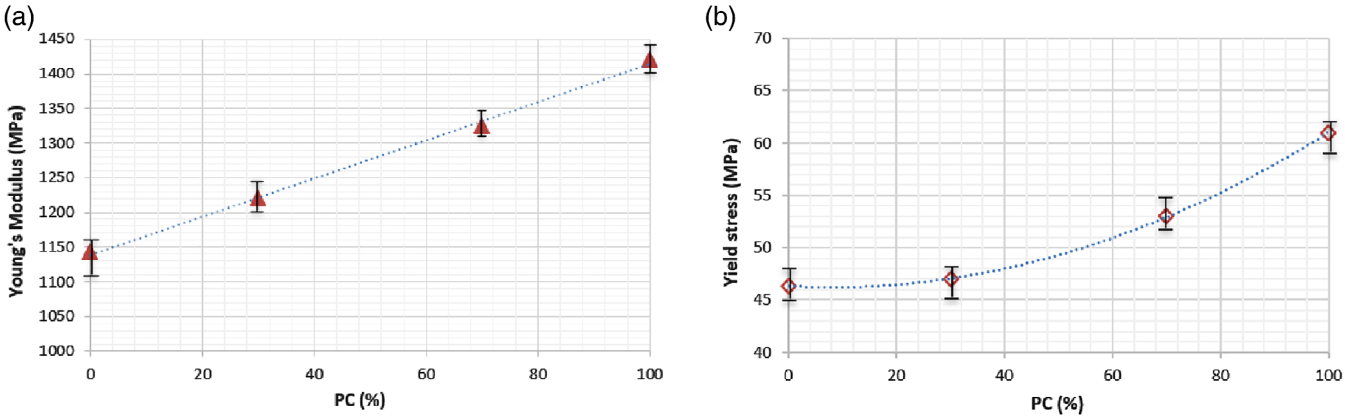


FIGURE 7 Evolution of Young's modulus (a) and the yield stress (b) versus the proportion of waste polycarbonate (PC) [Color figure can be viewed at wileyonlinelibrary.com]

Figure 7 shows the evolution of the Young's modulus and the yield stress of the four WEEE blends. It can be observed a synergistic effect with the addition of the waste polycarbonate, traduced by an improvement of both the yield stress and the elastic modulus. We recorded an increase of 24% in the modulus and 32% in the yield stress between the compositions ABS/PC (0/100) and (100/0). This improvement can be attributed to the good compatibility between the ABS and PC polymers in the blends. In literature, it has been postulated that the decrease of the modulus with the virgin ABS addition can be attributed to the tighter packing of the PC chains and the decrease of the molecular chain mobility of the PC by a secondary cross-linking, resulting thereby in a steric hindrance to the chain of the polymer.[24,25]

In Figure 8, a comparison between WEEE and virgin blends of ABS/PC is illustrated. In particular, we focus on the macroscopic mechanical properties derived from the tensile test, namely the yield stress, the Young's modulus, the elongation and stress at break. It was noticed in the light of the gathered results obtained on virgin blends subjcetd to the same tensile test that, in general, similar tendencies than the waste mixtures were observed. In addition, the comparison between virgin and waste blends highlights unanimously a degradation in the mechanical performances of the recycled ABS/PC blends. However, these results are not surprising since it is somewhat expected that aged materials would not exhibit the same performances as the new ones. Neverheless, it should be kept in mind that the main goal of recycling is rather to develop materials which can be reused and still useful despite their altered performances.

Again, the descending trend of the mechanical properties can be ascribed to the aging phenomenon of the materials derived from the end-of-life equipment which could have altered their performances. On the other hand, it shall be recalled that the ABS polymer is sensitive to thermo-oxidation due to its elastomeric matrix charged with the polybutadiene rubber.[26] This natural aspect it self can rend the recycling of ABS sometimes difficult and deteriorates the adherence between the phases and thereby the overall mechanical performances of the blend. Another explanation can also be related to the presence of BFRs in the waste polymers (Figure 2) which implies a poor compatibility with the present polymers. Some researches have illustrated the deterioration of the mechanical performances of polymer composites embedded with flame retardants.[27,28]

It was recorded a maximal loss of approximately 9% for the yield stress as well as 16% and 14% respectively, for the elongation and the stress at failure. But, this degradation can not limit the reuse of the waste blends whose ultimate properties remain still satisfactory and appropriate for many industrials fields.

Nevertheless, it was noticed an improvement of the Young's modulus of blends in comparison with the virgin ones as shown in Figure 8b. An increase of approximately 20% in the rigidity of the polymer blends was recorded. This finding can be correlated with the aforementioned DMTA results presented in Section 3.2. In fact, we mentioned before that the increase of the glass transition temperature (Figure 5) can be postulated to the increase of the stiffness of the chain polymer by aging phenomenon. Accordingly, the results depicted in Figure 8b confirm this hypothesis and corroborate the idea that the recycled materials are well stiffer than the virgin ones.

However, for a safe use of the recycled blends in industrial applications, attention should be paid regarding the overall mechanical behavior of these mixtures since it was noticed from the tensile test results a slight loss of the ductility with recycling. Thus, although recycling has enhanced

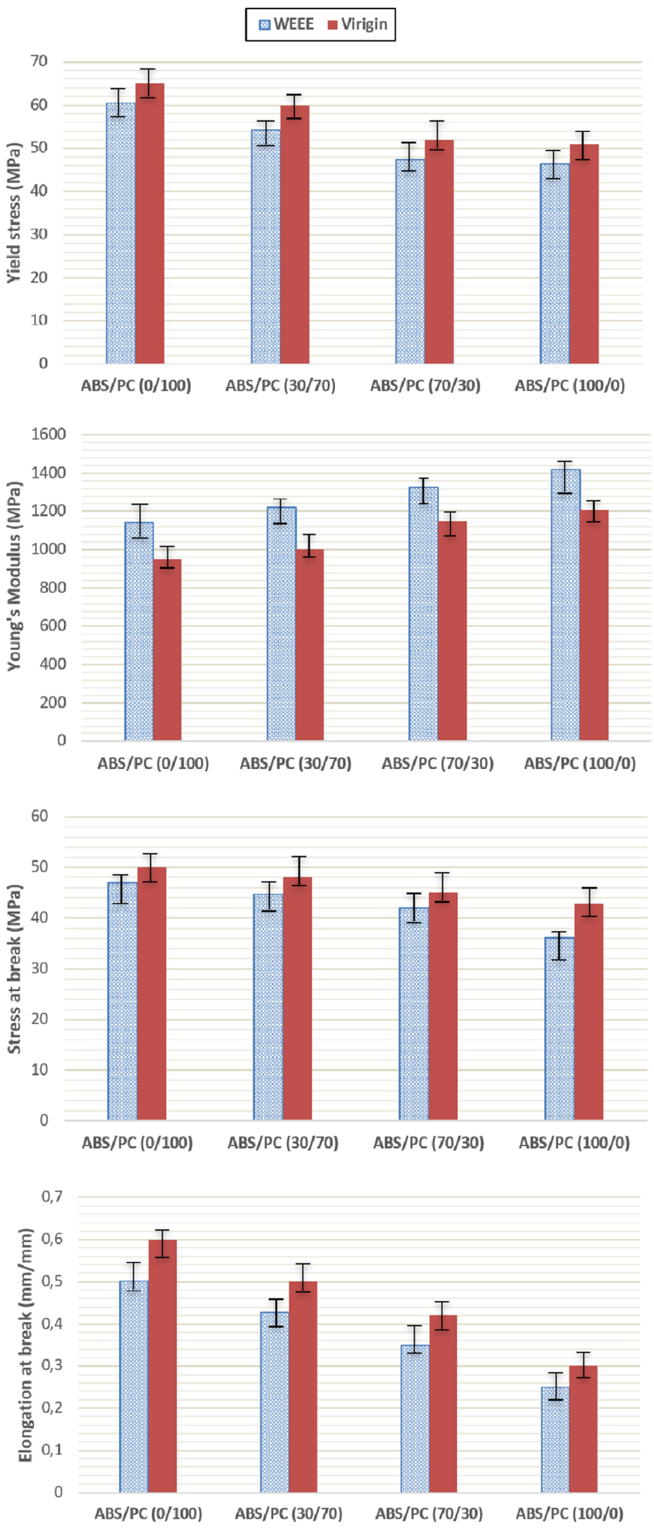


FIGURE 8 Comparison between wastes of electrical and electronic equipment (WEEE) and virgin acrylonitrile-butadiene-styrene/polycarbonate (ABS/PC) blends. From top bottom: Yield stress, Young's modulus, break stress, elongation at break [Color figure can be viewed at wileyonlinelibrary.com]

the rigidity of the polymer chains, the mechanical behavior is less ductile than the virgin materials and the failure could sometimes be fragile.

4 | CONCLUSION

In this paper, a contribution to upgrade the polymers derived form the end-of-life equipment is presented. The recycling process of ABS and PC polymers have led to blends of ABS/PC with acceptable mechanical properties. Many conclusions can be drawn in the light of the obtained results:

- The sorting and characterization of WEEE collected from four waste places in France have led to the identification of the predominant polymers to be recycled and investigated.
- The co-continuous morphology of WEEE ABS/PC blends have shown a good adhesion between the ABS and PC phases, thereby highlighting the compatibility between both waste polymers.
- The thermo-mechanical investigation corroborated the good compatibility between the ABS and PC waste polymers and showed that the intermediate compositions of ABS/PC blend (30/70) and (70/30) exhibit two glass transition temperatures, well shifted with respect to those of the two homopolymers.
- The comparison between the virgin and WEEE blends highlighted an increase of the glass transition temperatures for the recycled blends and stiffer mechanical behavior as confirmed by the tensile test. However, because of the combined aging and recycling phenomena, a decrease of the yield stress, the break stress and elongation was noticed, without compromising the ultimate performances of the waste blends since the mechanical behavior is still ductile and the macroscopic properties remain useful for a large range of industrial applications.

This study opens promising issues for the use and the upgrade of WEEE polymers in future. Although the good compatibility between the SAN matrix of the ABS and the polycarbonate on the one hand, and the good adhesion between the ABS and the polycarbonate, on the other one, work is now undertaken in order to better optimize the waste ABS/PC bends by the addition of a compatibilizer. The compatibilization process will be of interest to enhance the adhesion between the blend phases, reduce the interfacial tension surface and stabilize the morphology of recycled blends.[29]

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REFERENCES

[1] L. Zhang, Z. Xu, *J. Cleaner Prod.* **2016**, *127*, 19.
[2] A. Buekens, J. Yang, *J. Mater. Cycles Waste Manage.* **2014**, *16*, 415.
[3] Aîd, S. PhD. Thesis, ENSAM university, Paris, France, **2005**.
[4] G. F. Cardamone, F. Ardolino, *Waste Manage.* **2021**, *126*, 119.
[5] E. Mozos, A. Renteria-Bilbao, F. Díaz-Martín, *Appl. Sci.* **2020**, *10*, 4800.
[6] R. G. Charles, P. Douglas, I. L. Hallin, I. Matthews, G. Liversage, *Waste Manage.* **2017**, *60*, 505.
[7] J. Cui, E. Forssberg, *J. Hazard. Mater.* **2003**, *99*, 243.
[8] S. Aîd, A. Eddhahak, Z. Ortega, D. Froelich, A. Tcharkhtchi, *J. Appl. Polym. Sci.* **2017**, *134*, 44975. https://doi.org/10.1002/app.44975
[9] L. A. Utracki, *Polymer Blends Handbook*, Kluwer Academic Publisher, Amsterdam **2002**.
[10] R. Greco, L. Dong, *Macromol. Symp.* **1994**, *78*, 141.
[11] H. Lee, C. Shindo, *J. Appl. Polym. Sci.* **2021**, *138*, 50674.
[12] Nishino, K., Shindo, Takayama, T., Ito, H. *J. Appl. Polym. Sci.*, **2017**, *134*, 44550. https://doi.org/10.1002/app.44550
[13] B. I. Chaudhry, E. Hage, L. A. Pessan, *J. Appl. Polym. Sci.* **1998**, *67*, 1605.
[14] M. M. K. Khan, R. F. Liang, R. K. Gupta, S. Agarwal, *Rheol. J.* **2005**, *17*, 1.
[15] A. Guinault, C. Sollogoub, *Int. J. Mater. Form.* **2009**, *2*, 701.
[16] R. Krache, I. Debbah, *Mater. Sci. Appl.* **2011**, *2*, 404.
[17] R. Balart, J. Lopez, D. Garcıa, M. D. Salvador, *Eur. Polym. J.* **2005**, *41*, 2150.
[18] B. Majumdar, D. R. Paul, A. J. Oshinski, *Polymer* **1997**, *38*, 1787.
[19] M. Carrega, J. F. Agassant, M. Biron, C. Clozza, C. Duval, J. M. Haudin, C. Houdret, J. P. Machon, J. P. Queslel, B. Seguela, G. Villoutreix, R. Wirth, *Matériaux industriels - Matériaux polymères, Ed*, Dunod, France **2000**.
[20] J. H. Chun, K. S. Maeng, K. S. J. Suh, *Mater. Sci.* **1991**, *26*, 5347.
[21] N. Hadjichristidis, A. Hirao, Y. Tezuka, F. D. Prez, *Complex Macromolecular Architectures: Synthesis, Characterization, and Self-Assembly*, John Wiley & Sons, Asia **2011**.
[22] R. M. Wang, S. R. Zheng, Y. Zheng, *Matrix Materials*, Woodhead Publishing, Polymer Matrix Composites and Technology **2011**.
[23] R. Greco, M. F. Astarita, L. Dong, A. Sorrentino, *Adv. Polym. Technol.* **1994**, *13*, 259.
[24] A. Pavan, T. Riccò, M. Rink, *Mater. Sci. Eng.* **1981**, *48*, 9.
[25] R. D. Deanin, R. R. Geoffroy, *Org. Coat. Plast. Chem.* **1977**, *7*, 257.
[26] L. Xiadong, H. Bertilsson, *J. Appl. Polym. Sci.* **1999**, *74*, 510.
[27] Z. X. Zhang, J. Zhang, B. X. Lu, Z. X. Xin, C. K. CKang, J. K. Kim, *Composites, Part B* **2012**, *43*, 150.
[28] M. Sain, S. H. Park, F. Suhara, S. Law, *Polym. Degrad. Stab.* **2004**, *83*, 363.
[29] S. Tjong, Y. Z. Meng, *Eur. Polym. J.* **2000**, *36*, 123.

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