

# ENGINEERING JOURNAL

## Physical and Mechanical Characteristics of Kevlar Fiber-reinforced PC/ABS Composites

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**Abstract.** In this research, the laminated composites between the blend of polycarbonate (PC)/acrylonitrile-butadiene-styrene (ABS) and Kevlar fiber were prepared. The flexural and tensile properties of PC/ABS alloy and its composites were determined using a universal testing machine. The synergistic behavior of flexural modulus was observed for all regions of PC contents, while the synergism of flexural strength and tensile strength were found in some PC contents. It was found that the optimum weight ratio of PC:ABS was 60:40. In the Kevlar Fiber-reinforced PC/ABS composite system at PC:ABS of 60:40, both flexural modulus and strength were increased with matrix contents. Additionally, the flexural strength drastically increased with the matrix content and then reached the maximum value of 167 MPa at the matrix content of 33.4 wt%. The results from peel test, water contact measurement, and scanning electron microscopy (SEM) reveal that the interfacial adhesion between the Kevlar fiber and the polymer matrix could be improved by increasing the PC content in the matrix.

**Keywords:** Polycarbonate, acrylonitrile-butadiene-styrene, composite, Kevlar fiber.

**ENGINEERING JOURNAL** Volume 16 Issue 1

Received 3 September 2011

Accepted 27 October 2011

Published 1 January 2012

Online at <http://www.engj.org>

DOI:10.4186/ej.2012.16.1.57

## 1. Introduction

It has been well known that the alloy between bisphenol A polycarbonate (PC) and acrylonitrile-butadiene-styrene (ABS) is one of the most important commercial products for engineering applications [1-3]. The alloy, possessing many preferable properties, does not only minimize the disadvantages of pure PC (i.e. low chemical resistance, difficulty to process, high notch sensitivity, and easiness for stress cracking), but also introduce the other useful properties, such as glossiness and low-temperature toughness [4]. There are a number of patents and researches concerning the blend have been issued in the past [5-15], but the knowledge about its behavior is still limited because of the complexity of the system [16].

In many composite systems, the PC/ABS alloys have been selected to be used as matrix due to its ability to be tailor-made by varying their composition. Up till now, there are several researches focused on the composite of the PC/ABS matrix and reinforcing fillers such as carbon fiber, glass fiber, and montmorillonite [17-19]. However, there has not been a study on the PC/ABS alloy reinforced with Kevlar aramid fiber. The Kevlar fiber renders many outstanding properties. For instance, it has higher specific tensile strength than steel wire, industrial nylon, and polyester yarns. It also has a much higher tensile modulus than fiberglass, nylon, and polyester fibers. Furthermore, the Kevlar fiber possesses lower density than steel wire and glass fiber [20].

The aim of this study is to investigate the effects of the PC contents on the flexural and tensile properties of the PC/ABS alloy and the Kevlar-reinforced PC/ABS composite. Additionally, the interface between the matrix and the Kevlar fiber was observed via scanning electron microscope (SEM).

## 2. Experimental

### 2.1. Materials

Polycarbonate (PC) under the trade name of Makrolon<sup>®</sup> 2800 was supplied from Bayer Co., Ltd., while Acrylonitrile-Butadiene-Styrene graft copolymer (ABS), under the trade name of Lustran<sup>®</sup> 440 was provided from Lanxess (Thailand) Co., Ltd. The aramid fiber used in this study was Kevlar-29 plain weave type. The weight average molecular weights ( $\bar{M}_W$ ), number average molecular weights ( $\bar{M}_N$ ) and polydispersity index (PDI) of the chemicals are shown in Table 1.

Table 1. Average molecular weight of PC and ABS determined by gel permeation chromatography.

Component	$\bar{M}_W$ (g/mol)	$\bar{M}_N$ (g/mol)	PDI
PC2800	50482	27571	1.83
ABS	105251	51052	2.06

### 2.2. Preparation of polymer alloy

PC and ABS were dried at 100 °C for at least 6 hours in an air oven before PC was blended at the PC/ABS ratio varied from 80/20 to 20/80. Melt mixing of PC and ABS was carried out by a twin screw extruder (Rheocord 300p of Haake Inc.). The diameter and the length of the screw in the extruder were 16 mm and 400 mm, respectively. From the die head, the temperatures of five heating zones were set to 250, 250, 240, 230 and 220°C, respectively. The screw speed was fixed at 90 rpm.

### 2.3. Processing for testing samples

The blending pellets of PC and ABS were dried at 100°C for at least 6 hours in an air oven. Then they were processed by using a compression molder at 250°C under the pressure of 250 kg/cm<sup>2</sup>. The dimension of samples for flexural test was 25 mm × 60 mm × 3 mm.

PC/ABS film was produced using the same twin screws extruder. In the process, the extruder was equipped with film blowing die (LDPE-type die) with a diameter of 35 mm and a die gap of 1 mm. The molten polymer was extruded through the die and then was drawn up by nip rolls without air blowing. The molten polymer was cooled using an air cooling ring. Temperatures of five zones were set at 255, 250, 240, 230 and 220°C from die side, respectively. Screw speed was fixed at 90 rpm. The thickness of film was controlled by nip rolls take-up velocity. The draw ratio was estimated to be 10.

## 2.4. Composite processing

Kevlar-reinforced PC/ABS composites were manufactured by film-stacking method. The woven Kevlar fiber and PC/ABS film were cut and dried in an air oven. Then, the woven fibers and PC/ABS films were stacked alternately with a designed number of layers. The composites were made by hot pressing with compression molder at the processing temperature of 220°C and the pressure of 25 MPa for 30 minutes. The contact angle of each sample has been tested in order to control the wettability.

## 2.5. Sample characterizations

Flexural properties of the composites were determined using a universal testing machine (Instron, model 5567). Flexural tests were conducted according to ASTM D790M-93 standard. The test method used was a three-point loading by the support span of 48 mm. The crosshead speed during the flexural testing was 1.2 mm/min. At least five samples were used to determine the average property values. The tensile test was performed according to ASTM D638. The specimens of the test were fabricated in dog-bone shape.

The peel strengths of the composites were measured by the 180° peel test according to ASTM D903. At least five samples were used to determine the average property values.

The polymer matrices surfaces were characterized by the measurement of water contact angle measurement. The water contact angle is an indicator of the polarity and fiber wettability of the matrices which was measured by a sessile drop method at room temperature using a contact angle meter (Cam-plus Micro, Tanteq Inc.). Purified water droplet (2 $\mu$ l) was dropped on the sample surface by a micro-syringe and then the contact angle was measured immediately after placement on the polymer surface. Each reported value was averaged from 5-10 measurements.

The relationship between composition and intrinsic morphological characteristics of the blending systems and also the interfacial interaction between Kevlar fiber and polymer matrix was studied employing scanning electron microscope (JEOL-JSM 5800LV) at an acceleration voltage of 15 kV. The delamination surfaces of the composite specimens were gold sputtered (3 nm thickness) and dried in vacuum at room temperature. The obtained micrographs were used to investigate qualitatively the interfacial interaction between the fiber and the PC/ABS matrix.

In order to investigate morphology of PC/ABS blends, the flexural tested specimens were etched in an aqueous NaOH solution (30% w/v) at 150°C for 20 minutes to remove the PC fraction from their surfaces before obtaining the SEM micrographs.

## 3. Results and Discussion

### 3.1. Mechanical properties of PC/ABS matrix

Figure 1 shows the flexural modulus and strength of PC/ABS as a function of PC content. The flexural modulus of the PC/ABS alloys at various PC contents exhibited a positive deviation from the mixing rule. The flexural modulus in the alloy system at 40 wt% of PC was exhibited the highest value of 2.7 GPa, which was higher than the moduli of the parent polymers (2.4 GPa of PC and 2.5 GPa of ABS). The positive-deviation phenomenon in the modulus of these alloys could also be seen in some previous works (with different types of ABS) such as in the work of Lombardo *et al.* [21] and Menon *et al.* [22]. The existence of the inter-zones between the PC and ABS phases as discussed by Menon *et al.* [22] was probably attributed to the very good adhesion at the interface between the two components [16, 19]. The authors hypothesized the invoked diffusion of low  $\overline{M}_w$  species of SAN (Styrene-acrylonitrile) towards the PC domains resulting in certain compatibility between the SAN contained in the ABS and

the PC. Additionally, it can be seen that the flexural strengths of PC/ABS were found to increase with increasing PC in the blend (from 72 MPa of pure ABS to 100 MPa of pure PC). In addition, the strength of PC/ABS blend exhibited negative deviation from the mixing rule when the PC content was less than about 60 wt% of PC and then turned to positive deviation from the rule when the PC content was higher than 60 wt%.

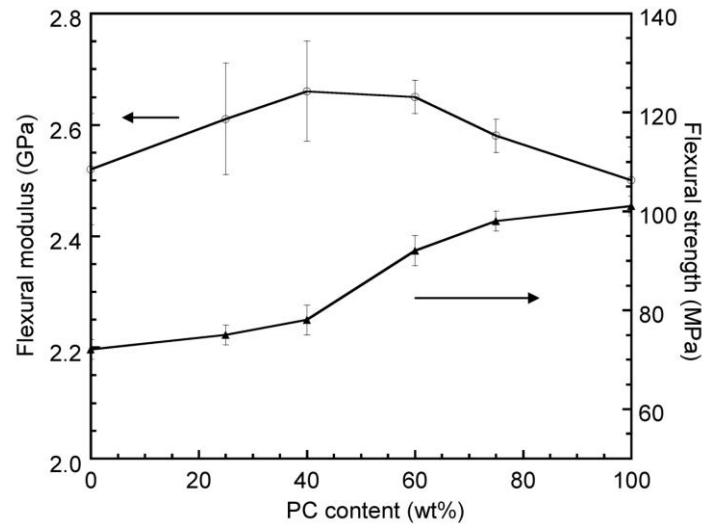


Fig. 1. Flexural modulus and strength of PC/ABS blends at various PC contents in PC/ABS matrix.

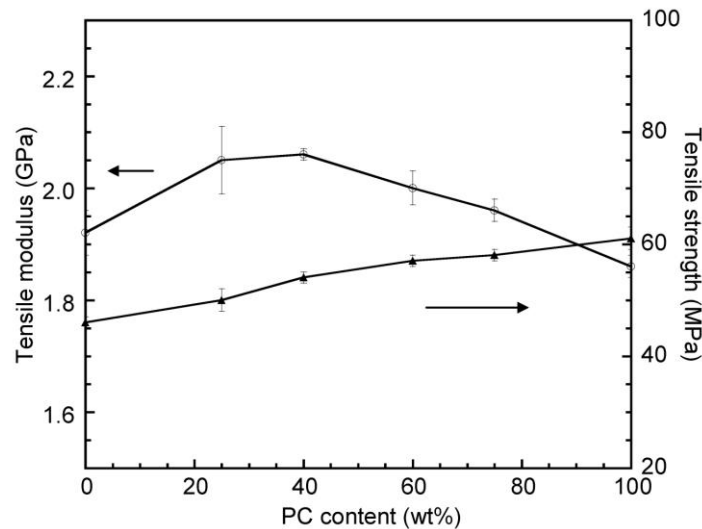


Fig. 2. Tensile modulus and strength of PC/ABS blends at various PC contents in PC/ABS matrix.

The relationships between the tensile properties of PC/ABS blends and PC content are shown in Fig. 2. It can be seen that the tensile modulus also exhibited positive deviation; furthermore, the highest modulus value of 2.1 GPa was observed in the blend system at approximately 40 wt% of PC (the same PC content for the synergistic behavior in flexural modulus). It can be seen that the tensile strength increased with increasing PC content in the PC/ABS blend from 46 MPa to 60 MPa of pure ABS and PC respectively. As seen in the figure, the increasing rate of tensile strength value was found to change at the composition range between 40 and 60 wt% of PC. In addition, the strength drastically increased from 46 MPa (of pure ABS) to 54 MPa (of the blend with 40 wt% of PC). For the further PC addition, the strength gradually increased to 60 MPa of pure PC. Moreover, elongation at break of the PC/ABS blends shown in Fig. 3 virtually unchanged in the range of 0-40 wt% of PC. The breaking strains at this range of PC contents were between 5 and 9 %. In the blends at the PC content of beyond 40 wt%, the breaking strain sharply increased with the PC content; the maximum value of 55 % was found at the PC

content of 75 wt%. Beyond this content, the breaking strain gradually decreased to 43% which is the value of pure PC. The variation of our breaking strain value corresponds with the result of B.S. Lombardo *et al.* [21].

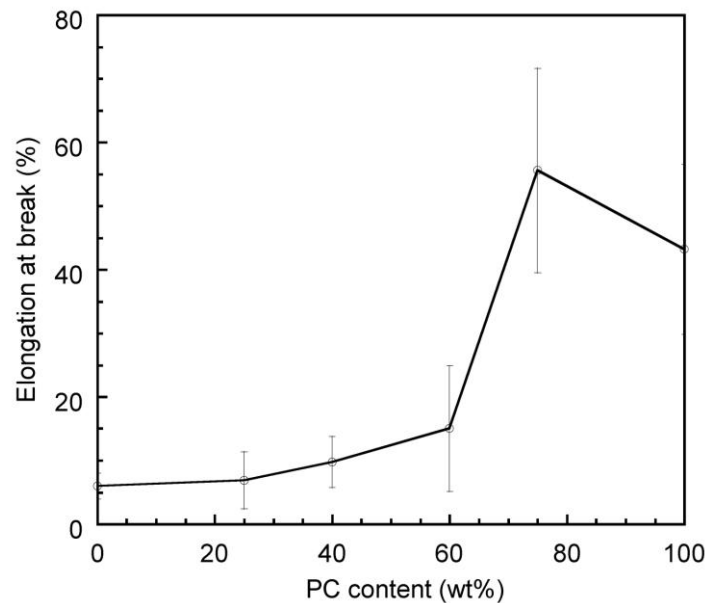


Fig. 3. Elongation at break of PC/ABS blends at various PC contents in PC/ABS matrix.

These remarkable behaviors of both flexural and tensile strengths of the blend involve with the phase transition. Normally, in the mixing of two immiscible polymers, two phase structure is usually formed. The component that occupy most volume of structure is called continuous phase and another phase is called dispersed phase. From Fig. 1, flexural strength of the blend displayed negative deviation from the mixing rule up to about 60 wt% of PC. This region ABS was found to be a continuous phase because there is an ABS-rich phase, and ABS also has lower viscosity than PC. Therefore, ABS tends to be encapsulation species. For further addition of PC, the strength turned to be positive deviation from the rule of mixing. In this region, PC performed as a continuous phase.

As seen in Figs. 1 and 2, both flexural and tensile modulus of the blend exhibited synergistic behavior. This phenomenon could be attributed to the fact that the low molecular weight fraction of ABS was able to dissolve in the PC domain, resulting in certain compatibility between the SAN contained in the ABS and the PC itself, and thus strengthening the ABS phase. This reason can be used to explain why the modulus of PC/ABS blends exhibited positive deviation from the rule of mixing.

## 3.2. Composite characterizations

### 3.2.1. Mechanical property measurement

To determine the most optimal polymer matrix content in the composite, the PC/ABS (60/40) films with varied thicknesses of 30, 40, 50, 100, 150, and 200  $\mu\text{m}$  were used for film stacking processing in the composite fabrication. These thicknesses made the PC/ABS matrix contents be 16.0, 19.2, 26.9, 33.4, 46.9, and 52.2 wt% respectively. Figure 4 reveals the flexural modulus and strength of Kevlar/PC/ABS composite as a function of the above matrix contents. Additionally, the flexural strength sharply increases with the matrix content and then reaches the maximum value of 167 MPa at the matrix content of 33.4 wt%. Beyond this content, the strength gradually decreases with increasing the matrix fraction. In addition, the flexural modulus of the composite as a function of matrix content also sharply increases with the matrix content and the highest modulus with the value of 15 GPa was acquired from the composite with the matrix content of 26.9 wt%. However, with increasing the matrix content beyond this ratio the modulus also decreases. The drastic increase of the flexural strength and modulus was due to the reduction of void content by increasing the quantity of polymer matrix to be able to penetrate into the Kevlar fabric. This might lead to the enhancement of the interaction between

the matrix and fiber. In the composite processing with the matrix content between 26.9-33.4 wt%, the polymer matrix was penetrated into the fabric at the highest level. However, the mechanical properties decreased for a further increase in the amount of the matrix.

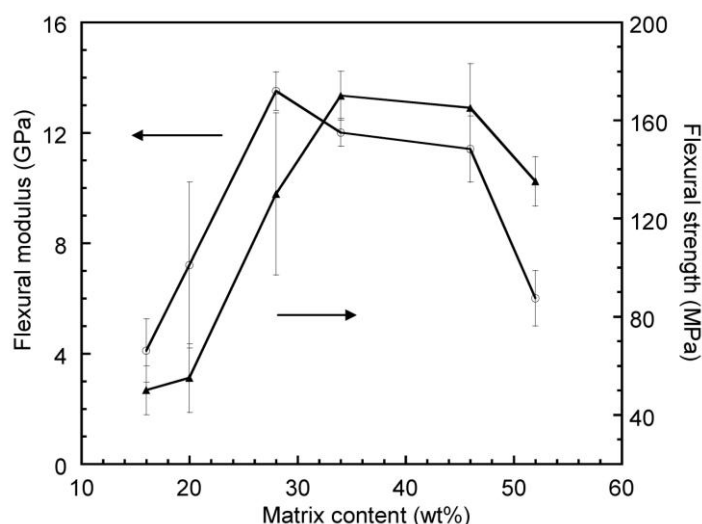


Fig. 4. Flexural modulus and strength of Kevlar/PC/ABS composite at various matrix contents.

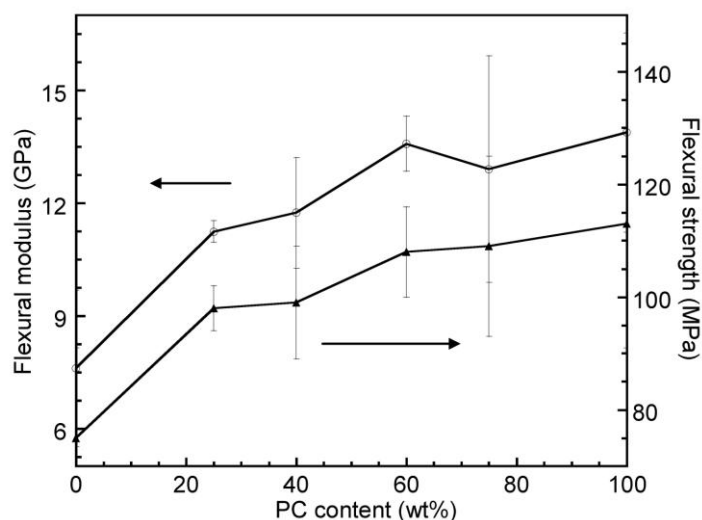


Fig. 5. Flexural properties of Kevlar-reinforced PC/ABS composites as a function of PC content in matrix.

The mechanical properties of fiber reinforced composite depend on several factors such as mechanical properties of each component and the fiber volume fraction. One of the important factors is the adhesion between the fiber and matrix. Figure 5 shows the flexural modulus and strength of Kevlar-reinforced PC/ABS composites as a function of PC content in the blend matrix. It can be seen that the modulus of the composites was systematically increased from 7.6 GPa (using pure ABS as a matrix) to 13.8 GPa (using pure PC as a matrix). From the prior experiment, PC/ABS blends exhibited synergistic behavior in flexural modulus. Therefore, the blends moduli were higher than those of the neat PC and ABS. However, the synergism was not observed in the case of Kevlar-reinforced PC/ABS. This discrepancy might be due to the fact that for the composite system, the adhesion between the reinforcing fiber and the PC/ABS matrices could play a major role in the flexural modulus of the composite. The flexural modulus curve implies that the adhesion between the Kevlar and the PC/ABS matrices could increase with increasing PC content in the matrices. It can be seen that flexural strength of the composites, which increased from 75 MPa (using pure ABS as a matrix) to 113 MPa (using pure PC as a matrix). The increase of the flexural strength of the composites might be influenced by the interfacial strength between the reinforced fiber and PC/ABS matrix and the flexural strength of the

matrix itself. The effects of interfacial strength on the mechanical properties of the composites could be observed in other systems such as in sisal-epoxy composites [23] and single-walled carbon nanotube reinforced copper matrix [24].

### 3.2.2. Investigation of adhesion between Kevlar fiber and PC/ABS matrices

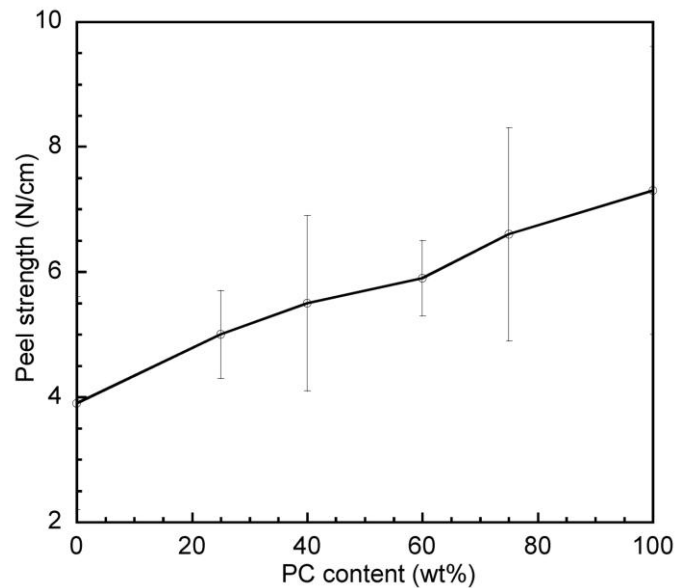


Fig. 6. Peel strength of the Kevlar-reinforced PC/ABS composites as a function of PC content in matrix.

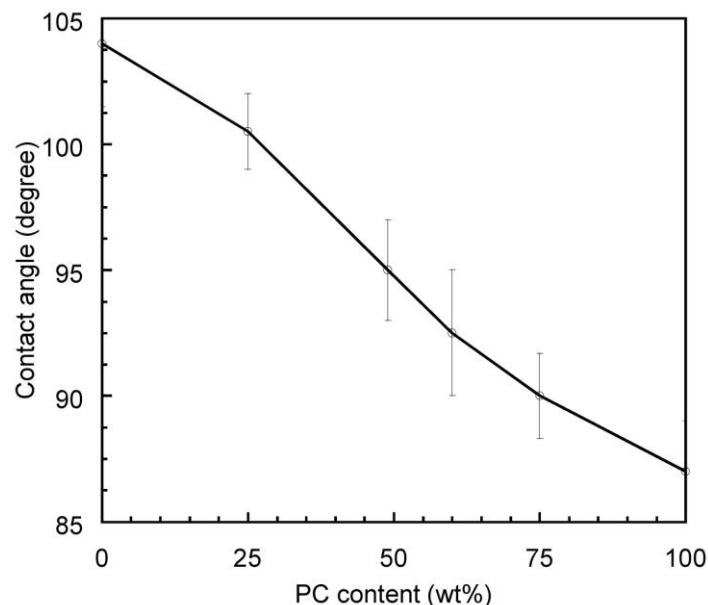


Fig. 7. Water contact angles of PC/ABS matrices at various compositions.

In order to confirm the flexural results and to investigate the adhesion between the Kevlar fiber and PC/ABS matrices, peel strength of the composites had also been evaluated. Figure 6 illustrates the peel strength of the composites as a function of PC content in the matrix. As seen in the figure, the peel strength gradually increased from 3.9 N/cm (using pure ABS as a matrix) to 7.3 N/cm (using pure PC as a matrix). This suggested that the interfacial adhesion between the Kevlar fiber and the polymer matrix could be improved by increasing the PC content in the matrix. The results also correspond with an increase of flexural modulus and strength with PC content as reported in the pervious section. The examination of the polarity of the PC/ABS matrices at varied composition of the blend was also

performed for good understanding of their interaction with Kevlar. Figure 7 depicts variation in water contact angles of PC/ABS matrices at various compositions. In general, material with low water contact angle represents high polarity material and vice versa. From the figure, we observed a decrease of water contact angles of PC/ABS matrices from  $104^\circ$  of pure ABS to  $88.4^\circ$  of pure PC i.e. the polarity of the PC/ABS increases with increasing the PC content in the blend.

From the mechanical behaviors and the polarity of PC/ABS blend, it can be concluded that polarity of the Kevlar fiber (Solubility Parameter ( $\delta$ ) = 23) and the polycarbonate (Solubility Parameter ( $\delta$ ) = 21) trend to be closer to each other than that to of ABS [25]. Therefore, the Kevlar-reinforced composite with greater PC content in the matrix exhibits higher compatibility between the fiber and the matrix. This is the reason why the peel strength and the flexural properties of the composite increased with increasing the PC content in the matrix. The relationship between compatibility and the enhancement of mechanical properties in this study corresponds to those for other systems reported in the literatures [26-28].

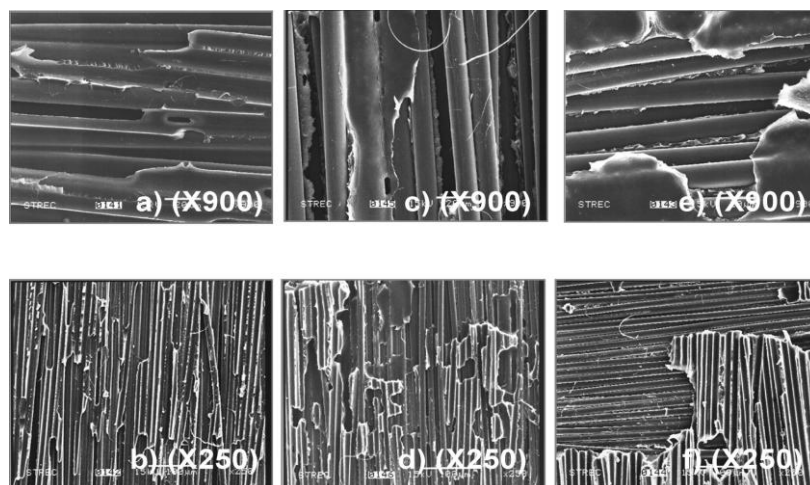


Fig. 8. SEM micrographs of Kevlar/PC/ABS composites at various matrix compositions: (a) and (b) pure ABS; (c) and (d) 40/60 PC/ABS; and (e) and (f) pure PC.

The morphologies of the peeled surfaces examined using SEM are shown in Figs. 8(a) to 8(f). The micrographs of the composite of ABS as matrix (Figs. 8(a) and 8(b)) exhibit high degree of interfacial failure implying that the fibers were easily stripped from the matrix material. It means that the adhesion between the Kevlar fibers and the ABS matrix is very poor. It can be seen from Figs. 8(e) and 8(f) that the composite used pure PC as a matrix rendered good adhesion between the Kevlar fiber and the matrix. This composite exhibited low interfacial or adhesive failure but rather high matrix failure i.e. cohesive failure. However, in Figs. 8(c) and 8(d), the composite with 40 wt% PC in the matrix displayed substantial degree of both matrix failure and interfacial failure. Moderate amount of stripped fibers was observed in this composite. It could be concluded that the Kevlar-reinforced 40/60 PC/ABS exhibited optimal level of interfacial interaction between the Kevlar fiber and the PC/ABS matrix for ballistic resistance.

#### 4. Conclusions

In the matrix study, the flexural modulus of the PC/ABS alloys at various PC contents exhibited a positive deviation from the rule of mixing. The highest modulus value of 2.7 GPa was observed in the PC:ABS ratio of 40:60. Furthermore, the flexural strength of PC/ABS alloys exhibited negative deviation from the mixing rule when the PC content was less than about 60 wt% of PC. The flexural strength then turned to positive deviation from the rule when the PC content was higher than 60 wt%. The tensile strength of the alloys increased with increasing PC content from 46 MPa (pure ABS) to 60 MPa (pure ABS). In addition, the increasing rate of tensile strength value was changed at the composition between 40 and 60 wt% of PC in the blend. In the composite system, the most optimum weight ratio of PC:ABS is 60:40. It was found that the flexural modulus and strength of Kevlar-



reinforced PC/ABS composite are increased with matrix contents. Additionally, the flexural strength sharply increases with the matrix content and then reached the maximum value of 167 MPa at the matrix content of 33.4 wt%. From the peel test, it reveals that the interfacial adhesion between the Kevlar fiber and the polymer matrix could be improved by increasing the PC content in the matrix.

## Acknowledgements

The authors would like to acknowledge the Thailand Research Fund (TRF) and the Higher Education Research Promotion and National Research University Project of Thailand, Office of the Higher Education Commission (AM1076A), for financial support of this project. Furthermore, additional supports are also provided by the 90<sup>th</sup> Anniversary of Chulalongkorn University Fund and the Funding from Thailand Graduate Institute of Science and Technology, NSTDA. The authors also would like to thank Bayer Co., Ltd. and Lanxess (Thailand) Co., Ltd. for their support of raw materials.

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