

# Foaming of an Immiscible Blend System Using Organic Liquids as Blowing Agents

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**ABSTRACT:** Foaming of blend systems is a promising approach to develop cellular materials with a set of desired properties. However, foaming of blend systems is not only a chance but also a challenge, as different polymers have to be foamed at the same foaming conditions. The best conditions during foaming are individual to each polymer and influence the obtained cellular structure. In immiscible polymer blends like poly(2,6-dimethyl-1,4-phenylene ether) (PPE) and poly(styrene-co-acrylonitrile) (SAN) the differences in glass-transition temperature ( $T_g$ ) and viscosity are vast and can inhibit the foaming of the blend system. In order to minimize the above-mentioned difference in  $T_g$  and viscosity, one approach is to choose a blowing agent, which shows a selective solubility in one polymer phase, working as a selective plasticizer. The aim of the present study is to evaluate systematically the foaming behavior of immiscible PPE/SAN blend systems using ethanol and *n*-pentane as blowing agents. Mass uptake of ethanol and *n*-pentane in the PPE/SAN-blends as function of the blend composition is measured, offering a selective solubility of ethanol in SAN, while *n*-pentane shows a high affinity to PPE. The plasticizing effect on the blend phases PPE and SAN is theoretically estimated using the Chow-equation and the WLF-equation. After foaming the blowing agent saturated blend samples in an oil-bath at different temperatures, the density reduction and the cellular structures are analyzed and correlated to the blend morphology, the blowing

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Figures 1, 3–7 and 9 appear in color online: <http://cel.sagepub.com>

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agent solubility in the blend phase, the rheological properties and the glass transition temperature of the nonsaturated and saturated blend phases.

**KEY WORDS:** blend, foam, ethanol, *n*-pentane.

## INTRODUCTION

**F**oaming of multi-phase polymer blends is regarded as a promising approach to tailor the foam properties. But, by foaming immiscible blend systems the factors influencing the foaming behavior also increase. Next to the properties of the blend phases, the rheological properties and the glass transition/crystallization temperature, the blend properties, e.g., the morphology, the viscosity ratio, or the interfacial tension, have to be taken into account [1–5]. Furthermore, the different processing windows of the blend phases often inhibit foaming [4].

Selective blending can be seen as one approach to narrow the processing windows of the blend phases by adjusting the rheological properties and the glass transition temperature of one blend phase [6–8]. But the phase properties and therefore the blend properties are changed permanently.

Using selective blowing agents is a second approach to adjust the processing windows of the blend phases and to improve the foaming behavior [5,9]. One effect of the type of blowing agent and the maximum solubility is the plasticizing effect, i.e. reducing the glass transition temperature and the viscosity of the polymer. During and after the foaming process the blowing agent diffuses out of the blend system. Therefore the duration of the plasticizing effect is directly correlated to the diffusion of the blowing agent out of the blend system [1–3]. As a result, the approach of using a selective blowing agent can be seen as a nonpermanent change of the blend properties compared to the use of selective blending.

The type and amount of blowing agent additionally influence further parameters of the foaming behavior [3,10–13]. The solubility of the blowing agent in the polymer directly affects the maximum achievable density reduction [1–3]. Furthermore an elevated decrease in solubility of the blowing agent in the polymer by increasing the temperature or decreasing the pressure is favorable as maximum amount of the blowing agent can be used for the foaming process [3]. It is also reported that an increased blowing agent content results in a higher cell density as a result of an increased nucleation rate [14–16]. Furthermore, the cell density is not only affected by the amount of blowing agent but also by

the diffusivity of the blowing agent in the polymeric matrix. A higher diffusivity favors a finer cell structure [2,3].

Today the influence of different blowing agents such as hydrocarbons, alcohols or inert gases is under investigation to improve the foaming behavior of polymers and polymer blend systems [1–3,12,17–23].

The aim of this study is to investigate the foaming behavior of an immiscible PPE/SAN using two different organic liquids (an alcohol and an alkane) as blowing agents. To gain an improved understanding of the foaming behavior of the complex multi-phase systems, the blend morphology, the blowing agent solubility in the blend phases as well as the rheological properties and the glass transition temperature of the nonsaturated and saturated blend phases are evaluated. The saturated blend systems are foamed at different temperatures using a batch-foaming approach and evaluated with respect to their foam structure and density reduction. Finally the achieved foam structure and the density reduction are correlated to the blend properties, the blowing agent content and the calculated plasticization.

## EXPERIMENTAL

In this work immiscible blends of poly(2,6-dimethyl-1,4-phenylene ether) (PPE PX 100F,  $T_g=216^\circ\text{C}$ ,  $\rho=1065\text{ kg/m}^3$ , molar volume:  $112.7\text{ cm}^3/\text{mol}$  (supplied by Mitsubishi Engineering Plastics, Europe) and poly(styrene-co-acrylonitrile) (SAN VLL 19,  $T_g=114^\circ\text{C}$ ,  $\rho=1070\text{ kg/m}^3$ , molar volume:  $88.1\text{ cm}^3/\text{mol}$ , from BASF SE) are used. As blowing agents, commercially available organic liquids such as an alcohol (ethanol; boiling point:  $78^\circ\text{C}$ , vapor pressure at  $20^\circ\text{C}$ :  $5.8\text{ kPa}$ ) and an alkane (*n*-pentane; boiling point:  $36^\circ\text{C}$ , vapor pressure at  $20^\circ\text{C}$ :  $56.2\text{ kPa}$ ) are taken.

The PPE/SAN blend systems are melt-compounded using a co-rotating twin-screw extruder (Brabender DSE 20/40) at a maximum processing temperature of  $260^\circ\text{C}$ . The composition of the prepared blend systems is shown in Table 1. As stabilizer, 0.1 wt% of Irganox 1010 is added. The melt compounded blend strands are cooled in a water bath and granulated afterwards.

To prepare the samples for the shear rheological characterization and the batch-foaming experiments, the granulated blend systems are

Table 1. Compositions of the melt-compounded blend systems.

PPE (wt%)	10	20	30	40	50	60	70
SAN (wt%)	90	80	70	60	50	40	30

grinded under liquid nitrogen (Pulverisette 14, Fritsch). Afterwards, the powder is compression molded (press: P/O/Weber) to discs (diameter: 25 mm, thickness: 1 mm) for the rheological investigation and to plates (side length: 120 mm, thickness: 1 mm) which are cut into samples of 15 mm × 15 mm × 1 mm for the absorption measurements as well as the batch-foaming experiments.

The shear rheological properties of the neat polymers and the blend systems are investigated by dynamic shear measurements. To identify the linear-viscoelastic region, dynamic strain sweep measurements with a deformation range from 0.1% to 100% at a frequency of 1 rad/s are performed first. The frequency of 1 rad/s has been used to be more accurate at low shear rates (Newtonian region) as no significant shear occurs during the batch-foaming experiments. As a strain of 5% is observed in the linear-viscoelastic region of both polymers for all investigated temperatures, it is chosen as strain for further rheological measurements. In a second step, the complex viscosity as function of the frequency in a range from 0.1 to 500 rad/s is measured at temperatures between 220°C and 280°C under nitrogen atmosphere. By using at least three curves of the complex viscosity as function of the frequency, master curves of the neat polymers at a reference temperature of 260°C are prepared. For all experiments, a Rheometric Scientific ARES RDA III with plate–plate configuration (plate diameter: 25 mm, gap: 1 mm) is used.

To correlate the transport properties of the blowing agents with the blend composition as well as the foaming behavior of the saturated blend systems, transmission electron micrographs of the blend morphologies are studied. Therefore a transmission electron microscope (TEM) from Zeiss type 902 with an acceleration voltage of 80 kV is used. Ultra thin samples are cut out of the quadrature samples for the absorption and foaming experiments using an Ultracut E from Leica. These ultra thin samples are stained for 30 s with osmiumtetroxide ( $\text{OsO}_4$ ) and 30 min with rutheniumtetroxide ( $\text{RuO}_4$ ). Due to the staining process, the PPE phase appears dark while the SAN phase is bright in the TEM-pictures.

Prior to the foaming trials, the mass uptake of blowing agent in the polymers and blend systems is analyzed via absorption experiments. Therefore always one sample of the neat polymer or the blend system is immersed into the liquid blowing agent in a gastight bottle. To saturate the samples, the bottles containing the polymer and blend samples in ethanol are heated up to 60°C using an explosion save vacuum oven while the bottles with *n*-pentane are stored at room temperature. These temperatures are chosen as they

are near the boiling point of the blowing agents. The saturation pressure is set by the vapor pressure of the blowing agent at the saturation temperature (ethanol at 60°C: 46.7 kPa; *n*-pentane at 20°C: 56.2 kPa) as the gastight bottles are closed under normal pressure. After defined times the samples are taken out of the blowing agent, cleaned and the mass uptake is measured using a microbalance MX 5 from Mettler Toledo.

The reduction of the glass transition temperature of the saturated polymers is estimated using the Chow-equation [24,25]. A lattice coordination number (*z*-value) of 2 is used for both polymers. The change in heat capacity at the glass transition of PPE and SAN is analyzed by DSC-measurements while the results of the prior absorption measurements are used for the weight fraction of the blowing agent in the polymer.

To evaluate the plasticizing effect on the complex viscosity a combination of the Chow-equation [24,25] and the WLF-equation [26] is used. Therefore, the temperature difference between the glass transition temperature of the nonsaturated and the saturated polymer is estimated by the Chow-equation and the shift factor for the temperature difference is calculated using the WLF-equation.

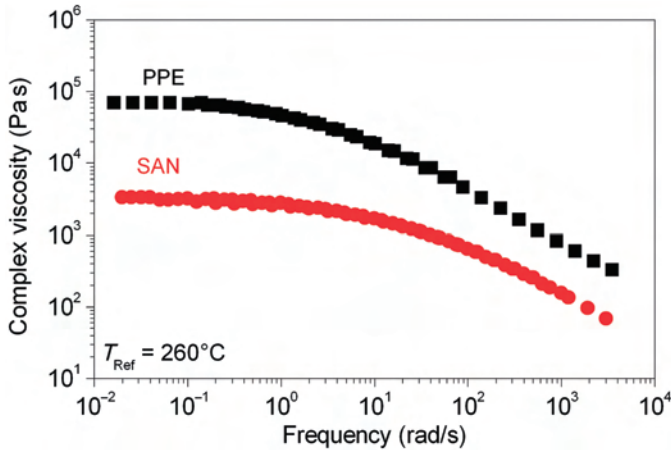
For the foaming experiments the samples are saturated as already explained above for the mass uptake measurements. Afterwards, the saturated samples are foamed at 160°C, 190°C and 220°C for 30 s by a batch-foaming approach using a calibration bath (Julabo, SE-14k). To stabilize the cell structure and prevent a further expansion or cell collapse the foamed samples are cooled down immediately in a water bath.

To establish a correlation between the transport as well as the blend properties with the foaming behavior, the foam density and the cell structure are investigated. The foam density is measured using the buoyancy method according to ISO 1183 for at least three samples and the average value is calculated. To evaluate the cell structure, scanning electron micrographs (SEM) are prepared using a Joel IC 848 with an acceleration voltage of 15 kV.

## RESULTS AND DISCUSSION

### Blend Characterization

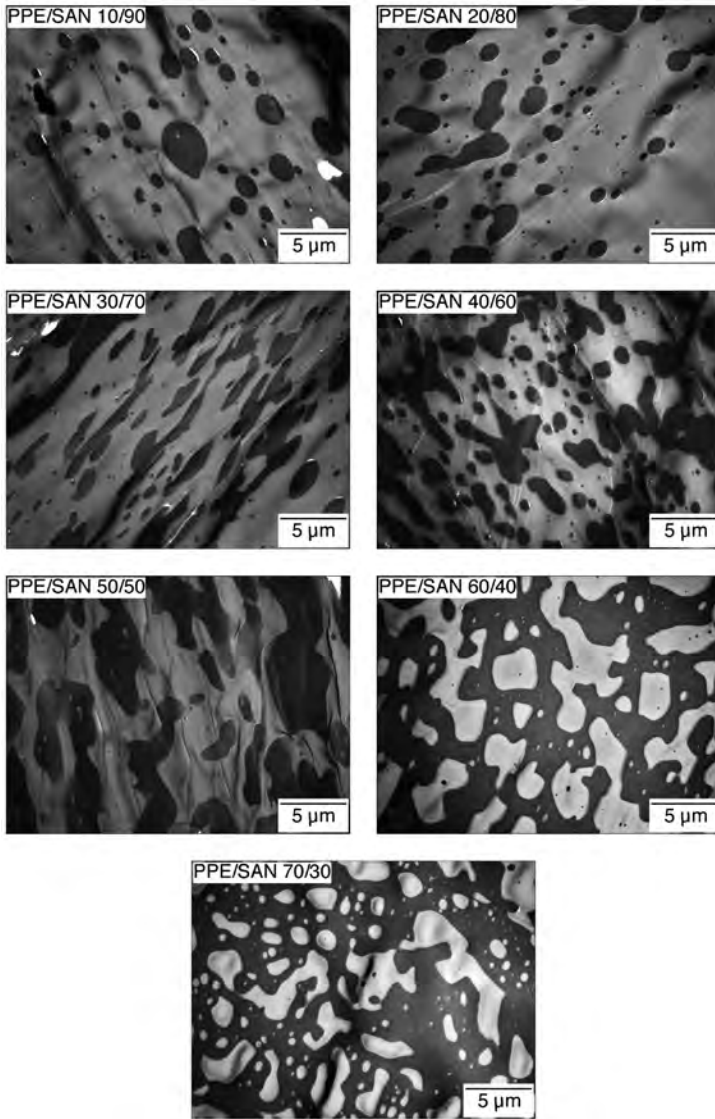
The shear rheological properties of the blend phases can be seen as one key factor of the processing windows of the blend phases. Figure 1



**Figure 1.** Master curves of the complex viscosity of PPE and SAN as function of the frequency at a reference temperature of 260°C.

shows the master curves of the complex viscosity of pure PPE and SAN at a reference temperature of 260°C. It is apparent that PPE has a higher viscosity compared to SAN all over the measured frequency range. The difference is more pronounced for low frequencies compared to high frequencies. However the large differences of the processing windows of PPE and SAN can be seen as limitation to foam immiscible PPE/SAN blends with an elevated PPE content [4].

Next to the influence on the processing window of the blend phases, the rheological properties are also a key factor for the development of the blend morphology, which is also known to highly influence the foaming behavior [2–4, 27]. According to the high viscosity of the PPE-phase a SAN-matrix phase can be expected to elevate PPE contents [28]. This can be verified by analyzing the transmission electron micrographs of the blend morphologies as shown in Figure 2. A SAN-matrix phase can be detected till 50 wt% SAN, while a further increase of the PPE-phase to 60 wt% shows the formation of first co-continuous blend morphologies. At an elevated PPE content of 70 wt% a PPE-matrix phase can be found. Therefore the phase inversion can be estimated in the range of 50–70 wt% of PPE. Based on these results a change in the transport properties and the foaming behavior is expected at a blend composition of 60 wt% PPE and 40 wt% SAN.



**Figure 2.** Blend morphology of the compression molded samples for the absorption measurements and the batch-foaming experiments as function of the blend composition. Due to the staining process PPE appears dark while SAN is shown bright.



## Polymer – Blowing Agent Interaction

The interaction between the neat polymers and the investigated blowing agents is theoretically evaluated by calculating the Hansen solubility parameters (dispersion part:  $\delta_d$ , hydrogen bonding part:  $\delta_h$ , polarity part:  $\delta_p$ ) using the following equations [29–31]:

$$\delta_d = \frac{\sum F_{di}}{V} \quad (1)$$

$$\delta_p = \frac{\sqrt{\sum F_{pi}^2}}{V} \quad (2)$$

$$\delta_h = \frac{\sqrt{\sum E_{hi}}}{V} \quad (3)$$

As the AN-content of the SAN is influencing the value of the Hansen solubility parameters, the parameters of both, the PPE and the SAN, are calculated according to table 4 in chapter VII of reference [31]. The solubility parameters of the used blowing agents are taken from table 9 in chapter VII of reference [31]. The calculated Hansen solubility parameters of the polymers as well as the parameters for the blowing agents are listed in Table 2.

The distance  $R$ , which represents the interaction between the polymer and the blowing agent can be obtained as:

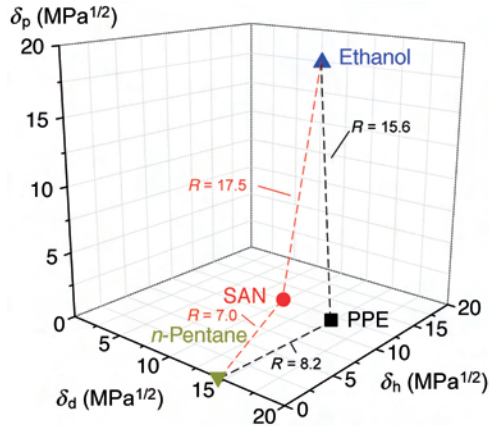
$$R = \sqrt{(\delta_{dp} - \delta_{dd})^2 + (\delta_{pp} - \delta_{pd})^2 + (\delta_{hp} - \delta_{hd})^2} \quad (4)$$

From literature it is known that a small distance ( $R$ -value) indicates an improved interaction between the polymer and the organic liquid [29–31]. The location of the neat polymers and the blowing agents as

Table 2. Calculated Hansen solubility parameters according to [31] chapter VII Table 4 (polymers) and Table 9 (blowing agents).

Material	Dispersion part (MPa <sup>1/2</sup> )	Hydrogen bonding part (MPa <sup>1/2</sup> )	Polarity part (MPa <sup>1/2</sup> )
PPE	19.6	5.2	3.7
SAN (19wt% AN)	18.0	2.3	5.6
ethanol	15.8	19.4	8.8
<i>n</i> -Pentane	14.5	0	0





**Figure 3.** Location and distance ( $R$ -value) of the neat polymers and the blowing agents in the Cartesian coordinate system of the Hansen solubility parameters.

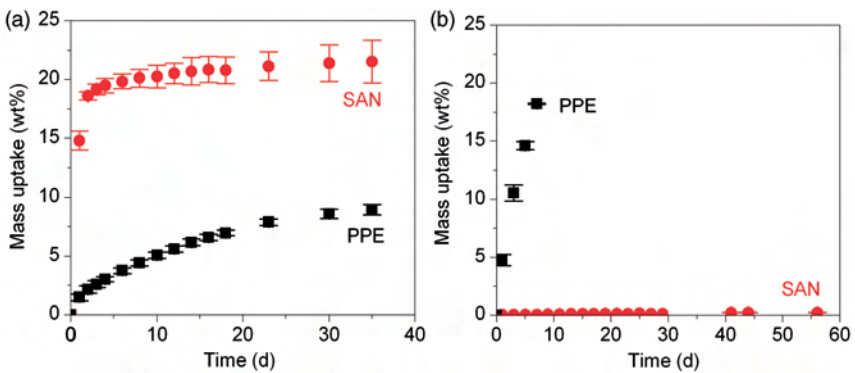
well as the distances between the polymers and the blowing agents are visualized in the Cartesian coordinate system in Figure 3. Taking the calculated  $R$ -values into account, both PPE and SAN show an improved interaction with  $n$ -pentane compared to ethanol. Therefore an elevated mass uptake of  $n$ -pentane can be expected in both cases. As PPE and SAN have a different sphere of solubility, no specific comparison between the two polymers is possible. As result no prediction of the difference in mass uptake between both polymers can be done. However, it can be concluded that  $n$ -pentane seems to be the promising blowing agent for both polymers.

### Blowing Agent Solubility

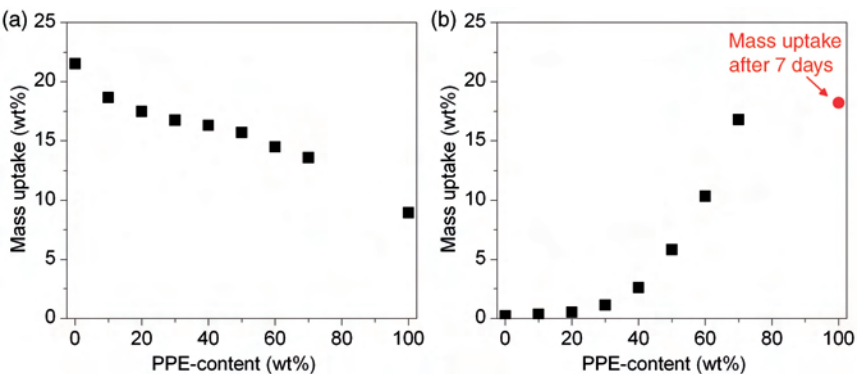
Comparing the theoretically calculated  $R$ -values with the results of the absorption experiments (Figure 4) a good agreement can be found in the case of PPE. As predicted by the Hansen solubility parameters, an improved mass uptake of  $n$ -pentane (18 wt% after 7 days) compared to ethanol (9 wt%) can be seen for PPE. However, an increasing number of cracks can be detected in the PPE sample during the saturation with  $n$ -pentane. This increasing number of defects result in a fracture of the sample after 7 days. Comparing the results of the absorption experiments with the theoretical prediction, a different behavior can be found for SAN. In disagreement to the theoretical prediction for SAN an elevated mass uptake of ethanol compared to  $n$ -pentane can be observed.

Only less *n*-pentane (0.2 wt%) is soluble in SAN while a mass uptake of 21.5 wt% could be detected for ethanol. It can be concluded that SAN acts as barrier material by using *n*-pentane as blowing agent [9].

The observed absorption behavior of the neat polymers is also reflected in their blend systems. Figure 5 shows the mass uptake of ethanol and *n*-pentane as function of the blend composition. As can be seen in Figure 5(a), the mass uptake of ethanol in the blend systems has a nearly linear dependence to the blend composition. As both phases of the blend systems, PPE and SAN, show a high mass uptake of ethanol no significant influence of the blend morphology is observed. A



**Figure 4.** Mass uptake of (a) ethanol at 60°C and (b) *n*-pentane at RT in the neat polymers PPE and SAN.



**Figure 5.** Maximum mass uptake of (a) ethanol at 60°C after 35 days and (b) *n*-pentane at RT after 56 days in PPE, SAN and their blend systems.

nonlinear behavior of the mass uptake as function of the blend composition can be detected for *n*-pentane. In this case, the blend morphology has a significant influence on the mass uptake as one of the blend phases acts as a barrier material (Figure 5(b)) [9]. Comparing the results of the absorption experiments of *n*-pentane with the transmission electron micrographs of the blend morphologies a dramatic increase of the mass uptake at the beginning of elongated PPE-domains can be detected. For low PPE-contents the SAN-matrix phase hinders the diffusion of the *n*-pentane in the blend system. In the region of the phase inversion from a SAN-matrix to a PPE-matrix, a significant increase in mass uptake can be seen. The SAN still hinders the diffusion of the blowing agent but the elongated PPE particles and, at elevated PPE contents, the PPE-matrix enable the diffusion of the *n*-pentane in the blend systems. Therefore, no significant density reduction is assumed by foaming SAN-rich blend systems using *n*-pentane as blowing agent as the blowing agent content limits the density reduction.

### Plasticizing Effect of the Blowing Agent

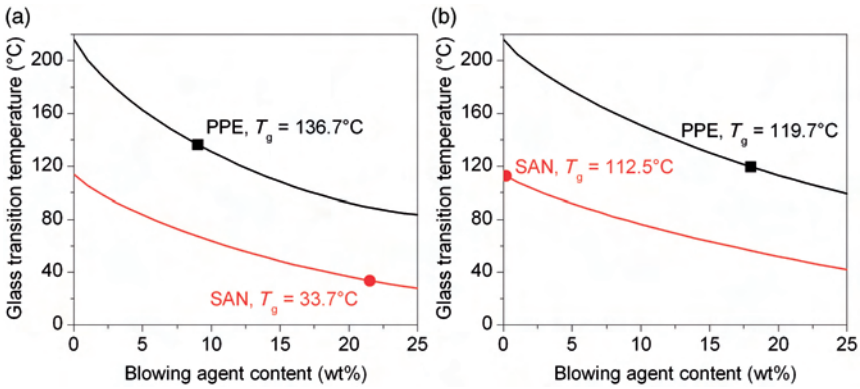
The earlier discussed type and the amount of blowing agent are responsible for the decrease of glass transition temperature and the reduction of viscosity and therefore the processing windows of the saturated blend phases. By using the Chow-equation, it is possible to theoretically estimate the glass transition temperature of the saturated blend phases [24,25]. The change in heat capacity at the glass transition ( $\Delta C_p$ ) of PPE and SAN is analyzed by DSC-measurements and listed in Table 3 together with the used glass transition temperature and the *z*-value for the polymers as well as the molecular weight of the polymers and blowing agents.

As can be seen by analyzing Figure 6(a), ethanol has an improved plasticizing effect on PPE compared to SAN. However, due to the lower solubility of ethanol in PPE compared to SAN, no significant difference

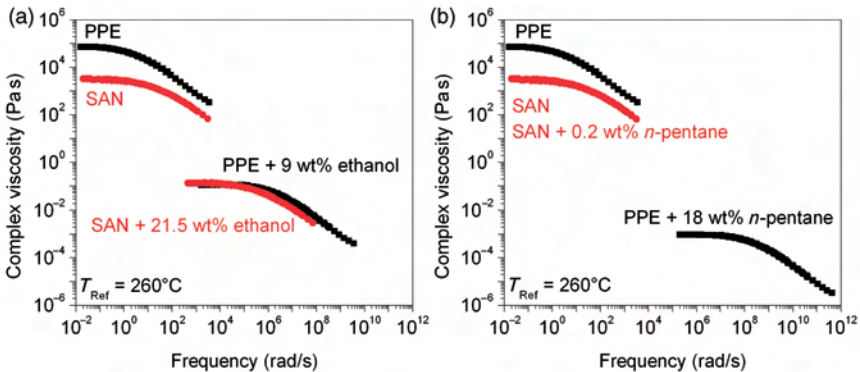
Table 3. Parameters used to calculate the plasticizing effect of the blowing agent on PPE and SAN.

Material	Change in heat capacity at $T_g$ (J/gK)	Glass transition temperature (K)	Molecular weight (g/mol)	<i>z</i> -Value
PPE	0.3	489	120.2	2
SAN (19 wt% AN)	0.45	387	94.3	2
ethanol	–	–	46.07	–
<i>n</i> -Pentane	–	–	72.15	–

of the glass transition temperature reduction can be found. In both cases the  $T_g$  reduction is in the range of 80°C. As a result the difference of the processing windows between the two polymers is not changed. Regarding the plasticizing effect of *n*-pentane, a similar behavior can be found for the overall plasticizing effect of the blowing agent. Still, an improved plasticization can be seen for PPE compared to SAN. Nevertheless, the elevated mass uptake of *n*-pentane in PPE leads to a



**Figure 6.** Theoretically calculated glass transition temperature of PPE and SAN as function of the (a) ethanol and (b) *n*-pentane content [24,25]. The data points show the calculated glass transition temperatures of the polymers taking into account the previous measured mass uptake of blowing agent.



**Figure 7.** Shift of the complex viscosity master curves of PPE and SAN due to the plasticizing effect of (a) ethanol and (b) *n*-pentane. The shift factor is theoretically calculated using the Chow-equation and the WLF-equation. To calculate the change in complex viscosity of PPE using *n*-pentane as blowing agent the mass uptake after 7 days is used.

significant reduction of the glass transition temperature in the range of 96.3°C while the glass transition temperature of SAN is reduced by only 1.5°C. As no complete saturation of PPE with *n*-pentane could be achieved, the last measured value of 18 wt% *n*-pentane (after 7 days) is taken to calculate the reduction of glass transition temperature.

As mentioned before, next to the glass transition temperature the rheological properties influence the processing windows of the respective blend phases. By combining the Chow-equation and the WLF-equation it is possible to estimate the change in complex viscosity of the saturated blend phases as function of the glass transition temperature reduction [24–26]. To shift the complex viscosity using the WLF-equation, first the constants  $C_1$  and  $C_2$  are calculated out of the frequency sweep measurements at different temperatures for both polymers. The calculated constants are listed in Table 4. The theoretically calculated shift of the complex viscosity for the observed saturation levels is highlighted in Figure 7(a) for ethanol and in Figure 7(b) for *n*-pentane as blowing agent.

Interestingly, a different behavior of the viscosity reduction compared to the change in glass transition temperature can be found for ethanol. As a result of the improved viscosity reduction of PPE a similar complex viscosity of PPE and SAN can be achieved (Figure 7(a)). Therefore the processing windows of the blend phases can be narrowed in case of the complex viscosity, but not in case of the glass transition temperature. In contrast to ethanol a contrary behavior can be observed for *n*-pentane analyzing Figure 7(b). While a similar glass transition temperature of the saturated blend phases PPE and SAN can be achieved using *n*-pentane as blowing agent (Figure 6(b)), a big difference in complex viscosity is observed. As can be estimated, due to the less *n*-pentane uptake of SAN, no significant change in complex viscosity is found. However, a significant reduction in complex viscosity of PPE below the complex viscosity of the saturated SAN can be seen using *n*-pentane as blowing agent. The described behavior leads to an increased difference in complex viscosity of PPE compared to SAN, although the difference in glass transition temperature is significantly reduced.

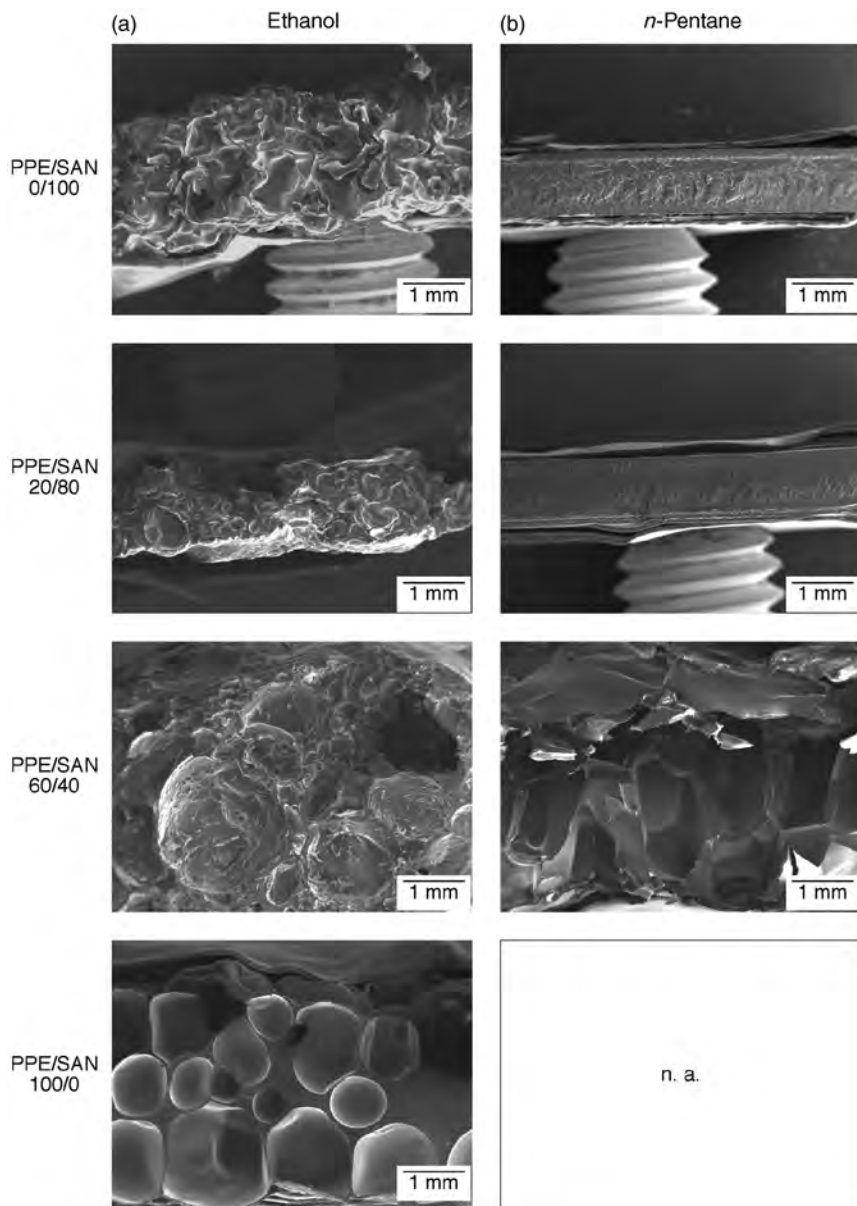
Table 4. Calculated WLF-constants.

Materials	$C_1$ (-)	$C_2$ (°C)
PPE	26.22	237.07
SAN	2.79	102.19

## Foam Evaluation

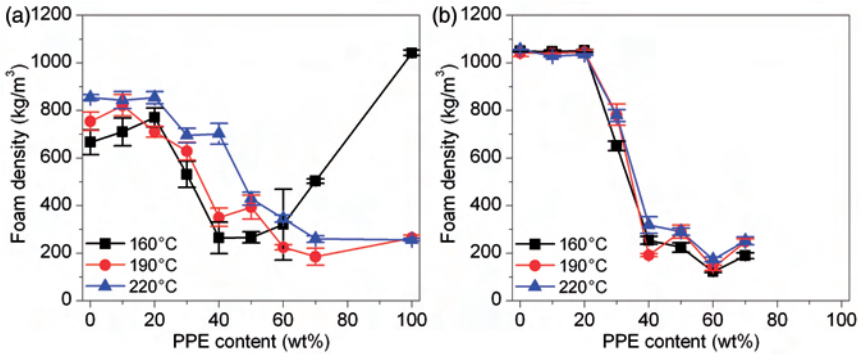
Summarizing the results of the absorption experiments and the theoretical calculations for ethanol as blowing agent, it should be possible to foam the neat polymers as well as all blend compositions. Both, PPE and SAN, show a good solubility of the blowing agent while the processing windows are narrowed in the case of complex viscosity. Regarding *n*-pentane, the solubility can be seen as key factor for foaming as it limits the plasticization of the polymer as well as achievable density reduction. The final foam structure of the neat polymers and the blend systems for a foaming temperature of 190°C and a foaming time of 30 s is highlighted in Figure 8, while the corresponding foam densities of all materials at the three investigated foaming temperatures are shown in Figure 9. Due to the cracking of neat PPE in *n*-pentane, no foamed PPE sample can be shown. Interestingly, for both blowing agents a decrease in foam density with increasing PPE content can be observed. Comparing this foaming behavior with the foaming behavior of the neat polymers and their blend systems using carbon dioxide as blowing agent as investigated by Ruckdäschel et al. [4], a significant difference can be observed. Ruckdäschel et al. achieved relatively high foam densities (above 500 kg/m<sup>3</sup>) for all investigated materials in the case of carbon dioxide as blowing agent and a foaming time of 30 s and a foaming temperature of 180°C [4]. For low PPE contents similar foaming behavior for ethanol and carbon dioxide as blowing agent can be observed. In both cases only elevated foam densities are achieved. As the used foaming temperatures are above the glass transition temperature of the nonsaturated SAN (114°C), cell coalescence and collapse can be expected even after no blowing agent remains in the polymer. Regarding *n*-pentane, the solubility can be seen as key factor for foaming SAN rich blend systems as it limits the achievable density reduction. While SAN shows only poor solubility of *n*-pentane (0.2 wt%) no foam cells (Figure 8(b)) and no density reduction (Figure 9(b)) can be observed for all investigated temperatures. As a result of the barrier properties of the SAN, only less *n*-pentane can diffuse in the immiscible blends (Figure 5(b)).

Increasing the high viscous PPE content leads to no significant density reduction in the case of carbon dioxide as blowing agent [4] while foam densities in the range of 200–300 kg/m<sup>3</sup> are achieved by using ethanol or *n*-pentane. The different properties of the blowing agents can be seen as reason for the differences in foaming behavior at elevated PPE contents. As a result of the lower diffusivity of larger molecules (organic liquids) in polymers compared to smaller molecules (carbon dioxide) a longer time is necessary to diffuse out of the material [3].



**Figure 8.** Scanning electron micrographs of the blend systems foamed for 30 s at 190°C using (a) ethanol and (b) *n*-pentane as blowing agent.





**Figure 9.** Foam density of the blend systems foamed at three different temperatures for 30 s using (a) ethanol and (b) *n*-pentane as blowing agent.

Therefore, the fast increase from the low viscosity of the plasticized PPE to the high viscosity of the nonsaturated PPE using carbon dioxide as blowing agent hinders the foam expansion [4]. The longer time ethanol and *n*-pentane plasticizing the high viscous PPE during foaming, result in an improved foam expansion and an elevated density reduction. Additionally the increase in complex viscosity with increasing PPE phase stabilizes the foam structure in the PPE/SAN blend systems. In the case of *n*-pentane as blowing agent the increase in PPE content additionally leads to improved blowing agent solubility in the blend systems and therefore an improved foaming behavior and a density reduction to around 200 kg/m<sup>3</sup>. The first foaming of the blend system is observed at a blend composition of 70 wt% SAN and 30 wt% PPE. Regarding the transmission electron micrographs, first, elongated PPE-domains can be detected at that blend composition. These domains seem to allow the blowing agent to diffuse into the blend system and to saturate the PPE domains near the surface also. At a blend composition of 60 wt% SAN and 40 wt% PPE, a density reduction similar to higher PPE contents can be observed indicating the start of the formation of a co-continuous blend morphology.

## CONCLUSION

A systematic study of the foaming behavior of an immiscible PPE/SAN blend system using two different organic liquids as blowing agents is presented. The blowing agent absorption in the neat polymers and the blend systems as well as the reduction of the glass transition temperature and the complex viscosity due to the plasticizing effect of the blowing

agent are analyzed in detail. For an improved understanding of the blowing agent absorption in the blend systems, the blend morphology is investigated via transmission electron micrographs. Finally, the achieved foam structure and the density reduction are correlated to the blend properties, the blowing agent content and the calculated plasticization.

The blowing agent absorption in the blend systems can be directly correlated to the absorption in the respective blend phases and to the blend morphology. Comparing the absorption of ethanol and *n*-pentane in the neat polymers PPE and SAN, a relatively high amount of ethanol is soluble in both polymers, while *n*-pentane shows a high solubility only in PPE. Therefore a nearly linear dependency of the blowing agent uptake from the blend composition and no significant influence of the blend morphology are found for ethanol. The poor solubility of *n*-pentane in SAN leads to a significant influence of the blend morphology, as SAN acts as barrier material. Therefore an elevated blowing agent uptake is detected only for elevated amounts of PPE. The increase in *n*-pentane absorption in the immiscible blend systems is observed in the region of the phase inversion from a SAN-matrix to a PPE-matrix.

Analyzing the reduction in glass transition temperature as result of the blowing agent absorption, an improved potential to plasticize PPE is found for ethanol as well as *n*-pentane. But, taking into account the higher solubility of ethanol in SAN compared to PPE, a similar  $T_g$  reduction in the range of 80°C is found for both. Nevertheless, calculating the reduction in complex viscosity using the Chow-equation and the WLF-equation, a similar complex viscosity is observed for PPE and SAN in the case of ethanol. In the case of *n*-pentane the poor solubility in SAN leads to no significant reduction of the glass transition temperature as well as the complex viscosity. Therefore a similar  $T_g$  and a significant difference in complex viscosity of the saturated polymers PPE and SAN are calculated.

The foaming behavior of the neat polymers and the blend systems directly reflects the blend phase properties and the observed polymer – blowing agent interactions. By using ethanol as blowing agent, the processing windows of the blend phases PPE and SAN are narrowed and a density reduction is achieved for all blend compositions. But the low viscosity and the foaming temperature above the glass transition temperature of the nonsaturated SAN lead to a poor stabilization of the foam structure, resulting in collapsing foam cells. By increasing the PPE content, the overall viscosity of the blend systems is increased and the PPE phase is found to stabilize the final foam structure.

Regarding *n*-pentane as blowing agent to foam the neat polymers and the blend systems, the poor solubility in SAN can be seen as key factor

for foaming. Therefore no density reduction is achieved at elevated SAN contents while the plasticizing effect of the blowing agent and the high solubility in PPE allows foaming PPE rich blend systems.

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