Nanoporous layered silicate AMH-3/cellulose acetate nanocomposite membranes for gas separations

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ABSTRACT

Nanoporous layered silicate/polymer composite membranes are of interest because they can exploit the high aspect ratio of exfoliated selective flakes/layer to enhance molecular sieving and create a highly tortuous transport path for the slower molecules. In this work, we combine membrane synthesis, detailed microstructural characterization, and mixed gas permeation measurements to demonstrate that nanoporous flake/polymer membranes allow significant improvement in gas permeability while maintaining selectivity. We begin with the primary-amine-intercalated porous layered silicate SAMH-3 and show that it can be exfoliated using a high shear rate generated by a high-speed mixer. The exfoliated SAMH-3 flakes were used to form SAMH-3/cellulose acetate (CA) membranes. Their microstructure was analyzed by small angle X-ray scattering (SAXS), revealing high degree of exfoliation of AMH-3 layers in the CA membrane with a small number of layers (4–8) in the exfoliated flakes. TEM analysis visualized the thickness of the flakes as 15–30 nm, and it is consistent with the SAXS analysis. The CO2/CH4 gas separation performance of the CA membrane was significantly increased by incorporating only 2–6 wt% of SAMH-3 flakes. There was a large increase in CO2 permeability with maintenance of selectivity. This cannot be explained by conventional models of transport in flake-containing membranes, and indicates complex transport paths in the membrane. It is also in contrast to the much higher loadings of isotropic particles required for similar enhancements. The present approach may allow avoidance of particle aggregation and poor interfacial adhesion associated with larger quantities of inorganic fillers.

1. Introduction

The demand for higher-performance gas separation membranes is rapidly emerging because of their potential to reduce energy consumption in chemical processing. Polymeric membranes possess the limitation of a trade-off between selectivity and productivity [1]. Inorganic molecular sieve (e.g., zeolite) membranes are being developed as an alternative due to their highly selectivity and permeability [2,3]. Despite their promising characteristics in gas separation, defect-free zeolite membranes are presently difficult to synthesize economically on large scale. Hence, composite/hybrid (‘mixed matrix’) membranes are widely being studied to overcome the limitations of polymeric and zeolite membranes and best combine the advantages of each type of material [4]. Various inorganic porous materials such as zeolite, metal oxide nanotubes, and metal organic frameworks (MOFs) have been incorporated in polymers, and show varying degrees of enhancement in separation performance [5–8]. However, control over the interfaces between the inorganic and polymeric materials is found to be a critical but difficult issue. Moreover, it is found that high (30–60 wt%) loadings of the inorganic materials are often necessary to produce substantial improvements in membrane performance [9,10]. While recent progress has been made towards resolving these issues [11,12], it remains unclear whether such membranes can be reliably fabricated on a large scale with high loadings of inorganic materials and a low density of defects.

Another approach towards hybrid membranes involves the use of the ‘selective flake’ concept, utilizing nanoporous layered silicates incorporated in polymer membranes [13,14]. This relatively recent concept is illustrated in Fig. 1. The distinctive geometrical features of layered materials, i.e., small thickness and high aspect ratio, are hypothesized to provide large increases in separation performance with the presence of only a small amount of inorganic material. For example, the high aspect ratio can decrease permeability of larger gas molecules (too large to pass through the nanopores) by requiring a highly tortuous path around the layers. At the same time, the small thickness of layered materials could improve the permeability of smaller gases due to a
much lower diffusion resistance than thicker bulk filler particles [13]. These combined effects are expected to lead to highly permeable and selective gas separation membranes with only small loadings of the layered material. Furthermore, nanometer-thin layered materials are more amenable to the fabrication of submicron membranes (e.g., the incorporation of layered materials in skin layers of hollow fiber membranes) [15].

Several types of nanoporous layered materials are now known, such as the layered silicates MCM-22, UZAR-S1, and Nu-6 [16–18], layered aluminophosphates (AlPOs) [13], and layered borogermanates [19]. The nanoporous layered silicate AMH-3 was chosen for this study [20]. AMH-3 is a 3-D porous layered silicate with 8 membered ring (MR) pores, and its crystallographic pore size of 3.4 Å can potentially be useful for several important gas separations such as CO2/CH4 and H2/N2. AMH-3 was first synthesized and characterized in 2003 [20]. Several challenging issues must be overcome before the fabrication of AMH-3/polymer composite membranes with high separation performance can be achieved. The first hurdle was regarding the swelling of the material to increase the interlayer spacing. Unlike conventional nonporous clay materials, AMH-3 has ordered silanol groups on the layer surfaces, accompanied by charge-balancing cations in the interlayer spaces [21]. These Sr2+ and Na+ cations form strong ionic bonds. Furthermore, interlayer condensation may occur during exchange of these cations with protons. Conventional swelling processes used for clays were not successful for AMH-3. Hence, a new swelling process for AMH-3 was first developed by Choi et al. [22]. The swollen AMH-3 (SAMH-3) material was incorporated in polybenzimidazole (PBI) membranes for H2/N2 separation [23] and into Nafion® proton exchange membranes to reduce methanol crossover [24]. Recently, we reported more detailed processes for swelling and silylation of AMH-3 while preserving its pore structure to a greater extent [25]. However, none of the above reports showed clear increases in the performance of polymeric membranes upon incorporation of SAMH-3. Furthermore, no clear evidence existed regarding the exfoliation and dispersion of SAMH-3 as high-aspect-ratio layers.

In the present work, we address the challenge of exfoliating SAMH-3 and processing it into a hybrid membrane with higher performance than a polymeric membrane. The previous studies on SAMH-3/polymer composite membranes used conventional dispersion techniques such as ultrasonication and mixing via stirring with a magnetic bar. These mild shearing processes cannot guarantee a high degree of exfoliation of SAMH-3 layers in the polymer matrix. Here, we fabricate SAMH-3/cellulose acetate (CA) membranes by a different route. CA is a polymeric material currently used to fabricate hollow fiber membranes for natural gas separation [26,27]. We show that a high-shear mixer with a high-speed rotating impeller can effectively exfoliate SAMH-3. The angular speed of the impeller is 7000 rpm, thereby generating a high shear rate estimated at 733 s⁻¹. We conduct a microstructural analysis of the SAMH-3/CA composite membrane by small-angle X-ray scattering (SAXS) and transmission electron microscopy (TEM), and demonstrate that a high degree of exfoliation has occurred. We then show that the CO2/CH4 gas separation properties of the hybrid membranes, in particular an enhancement in the CO2 permeability while maintaining the CO2/CH4 selectivity, are substantially enhanced over pure CA membranes. These unambiguous results represent a demonstration of the concept of ‘high-aspect-ratio, low-loading, flakes’ in the formation of composite membranes.

2. Experimental section

2.1. Synthesis of swollen AMH-3 (SAMH-3)

Dodecylamine-swollen AMH-3 (DA-SAMH-3) was prepared as reported by us elsewhere [25]. Typically, AMH-3 crystals were synthesized by hydrothermal synthesis for 3 days. The molar composition of the reactant gel was 1 TiO2: 10 SiO2: 2 SrCl2: 14 NaOH: 675H2O. To prepare this gel, 1.38 g of sodium hydroxide (Aldrich) was dissolved in 55.85 g of DI water. After 30 min of stirring, 2.94 g of strontium chloride (99%, Aldrich) was added. The reactant sol became clear after 30 min stirring at 80 °C. Then, 12.52 g of sodium silicate (26.5% SiO2, Aldrich) was added. After 30 min stirring, 4.25 g of titanium chloride (Fisher Scientific, 20%, HCl stabilized) was added drop-wise, and stirred for 1 h. After 3 days of hydrothermal reaction at 200 °C, the AMH-3 crystals were separated by sedimentation and decantation. To swell AMH-3, the sequential intercalation method was used. Typically, 0.776 g of DL-histidine (≥99%, Aldrich) was dissolved in 25 ml of DI H2O at 60 °C. Then the clear solution was cooled to room temperature and the pH was regulated to 6.0 by adding several drops of HCl (36.5%, Aldrich). This clear solution acts as a buffer to provide protons for entry between the AMH-3 layers. Then, 0.2 g of as-made AMH-3 was added to the buffer solution to start proton-exchange of the metal cations present between the AMH-3 layers. In the meantime, the swelling agent solution was prepared by dissolving 2.061 g of dodecylamine (Aldrich) in 50 ml of DI H2O at 60 °C followed by 30 min stirring. After 1 h from the start of proton exchange, the swelling agent solution was added drop-wise. After 10 h of stirring, swollen DA-SAMH-3 was obtained. It was purified by washing and centrifuging with DI water several times.

2.2. Fabrication of SAMH-3/cellulose acetate (CA) composite membranes

Tetrahydrofuran (THF) was chosen as the solvent for CA. Its evaporation rate is sufficiently slow to allow time for uniform formation of the polymer after casting on a glass plate. A certain amount (e.g., 62.5 mg for 4 wt% SAMH-3/CA composite) of SAMH-3 particles was added to 8.5 g THF followed by 30 min ultrasonication.
was embedded in epoxy resin and cured for 1 day. The cured sample 2000 operating at an accelerating voltage of 200 kV. For high-resolution Transmission Electron Microscopy (TEM) images were taken with a Hitachi HF-2000 operating at an accelerating voltage of 200 kV. Powder XRD patterns were obtained with a Panalytical X’Pert Pro diffractometer operating with a Cu source (λ = 1.5418 Å) and an RTMS detector. A narrow divergence slit (1/32°) and an anti-scattering slit (1/16°) were used. Scanning Electron Microscopy (SEM) images were obtained with a Hitachi HF-2000 operating at an accelerating voltage of 200 kV. For high-resolution TEM images, a JEOL 4000 EX was used at an accelerating voltage of 300 kV. To obtain cross-sectional images of composite membranes that show the presence of AMH-3 flakes in CA composite membrane, the DA-SAMH-3/CA composite membrane was embedded in epoxy resin and cured for 1 day. The cured epoxy mold was micromoulded to 80–100 nm thickness with a 35–angled diamond knife.

2.4. Gas permeation

The CO2/CH4 separation performance for each sample was evaluated using an equimolar feed mixture of CO2/CH4 based on a standard isochoric (constant-volume, variable pressure) technique [28]. Mixed gas permeation results are more practical than the corresponding single gas data since they include possible non-ideal effects such as competitive diffusion and adsorption. The upstream pressure was monitored using a 1000 psia Sensotec SC Series pressure transducer. The pressure in the downstream volume was measured using a 10 Torr MKS Baratron® (Type 127) pressure transducer, and the permeate was sent to a gas chromatograph (Varian 450) for analysis. The output from the downstream pressure transducer was interfaced with a personal computer using LabView® data acquisition software for real-time data recording. The entire permeation system was maintained to within ±0.1 °C using a proportional controller (Cole Parmer, BA-2155-54). Several measurements were performed for the thickness of each sample by using a micrometer (Ames, Waltham MA, Model #56212) and their arithmetic averages were used for permeation data analysis. Three independent membrane samples were fabricated at each SAMH-3 loading, and the permeation data from these samples was averaged.

3. Results and discussion

3.1. SAMH-3 exfoliation

Swollen AMH-3 (SAMH-3) was prepared by hydrothermal synthesis and the sequential intercalation method, as explained in Section 2. For the preparation of exfoliated and dispersed layered silicates, procedures such as high-shear melt blending using a twin screw extruder [29,30], or direct intercalation of polymer chain between layers using in-situ polymerization [31,32], have been reported. However, these processes are not easily applied to the fabrication of CA/SAMH-3 composite membranes due to the rigidity and poor melt-processability of cellulose acetate. For effective exfoliation of SAMH-3 particles, a high-shear mixing process was adopted. For comparison, we also performed conventional vortex mixing of SAMH-3 in water. Fig. 2a shows an SEM image of the morphology of SAMH-3, which consists of collections of swollen layers into sheets, with mesoscopic spacing between the sheets. The approximate molecular structure (deduced from XRD, NMR, and IR) of SAMH-3 was previously reported elsewhere [25]. In vortex mixing, 10 mg of SAMH-3 particle was added to 1 g of water and placed in the vortex mixer for 15 min. Fig. 2b shows the surface morphology changes in SAMH-3 after vortex mixing in water. The spacing between some of the sheets of SAMH-3 was significantly increased and the onset of exfoliation is seen. Fig. 2c shows the result of the vortex mixing process for SAMH-3 in tetrahydrofuran (THF), which is the solvent used in this study for fabrication of nanocomposite membranes. The result is similar to that obtained in water. One difference between the two cases is the observation of small clusters of material on the SAMH-3 surface after vortex mixing in THF. This is believed to be due to the extraction of the swelling agent by THF and deposition on the SAMH-3 external surface. The degree of exfoliation is dominated by the shear stress acting on the SAMH-3 layers rather than chemical affinity between the solvent and the layers. The two solvents used for vortex mixing were DI water and THF, both of which have low viscosities (~10^-3 Pa-s). The results in Fig. 2b and c also suggest that if a high-viscosity polymer solution is used instead of water, further exfoliation might occur to the large increase in shear stress on the sheets.

3.2. DA-SAMH-3/CA composite membranes

SAMH-3/CA composite membranes were fabricated using a high shear mixer at 7000 rpm, as described in Section 2. The viscosity of the SAMH-3/polymer dispersion was about 30 Pa-s [33]. Fig. 3a shows the XRD pattern of SAMH-3 particle, and Fig. 3b–e shows the wide angle X-ray scattering (WAXS) patterns of membranes with different SAMH-3 loadings (0–6 wt%). Characteristic high-2θ, low-intensity, Bragg peaks of SAMH-3 particles (marked with asterisks) are still visible after their incorporation in CA membranes, indicating that the internal structure of the SAMH-3 layers was preserved in the mechanical exfoliation process. The present WAXS and XRD patterns do not cover the low-2θ Bragg peaks. Due to the low intensity of the high-2θ peaks, they cannot be quantitatively analyzed. Quantitative information on the exfoliation of SAMH-3 stacks can only be determined by analyzing the lower Q-region (0.005–0.2 Å−1). Small angle X-ray and neutron scattering (SAXS/SANS) have been widely used for analyzing microstructure and morphology of polymeric materials. For example, they give detailed information regarding the structure of ionomers such as Naftion® and sulfonated polyimides, such as the size and orientation of water nanochannels [34,35]. The structure and morphology of cellulose acetate membranes has also been studied by SANS, and results comparable to transmission electron microscopy (TEM) are obtained [36]. Based on the geometry of inorganic fillers (e.g., sphere, disk, or rod), different X-ray/neutron scattering models have been developed to fit experimental intensity data and obtain morphological information on the inorganic fillers [37,38]. We measured SAXS patterns of SAMH-3/CA composite membranes with different loadings of SAMH-3, and performed detailed fitting simulations...
to obtain the morphological parameters of the dispersed SAMH-3 layers. The simulations were performed with the IGOR Pro program containing the scattering model packages (obtained from the NIST Center for Neutron Research) [39]. The stacked-tactoid model was adopted for the membranes [40]. The governing SAXS intensity equation, and the form factor/structure factor models, are given in Eqs. (1)–(5), [38,39]. The form factor \( P(Q) \) includes the particle size and orientation, and the structure factor \( S(Q) \) describes the structure of the stacks via the interlayer spacing and the average number (and Gaussian variance) of layers in the stacks. The SAXS intensity also depends on the number density of AMH-3 plates and the electron density difference between the silicate, interlayer space, and the polymer matrix.

\[
\rho_{\text{final}}(Q) = N_{\text{SAMH}} \int_0^{\pi/2} \left[ \Delta \rho_{i}(V_i f_i(Q) - V_j f_j(Q)) + \Delta \rho_c V_c f_c(Q) S_c(Q) \psi(Q) \sin \phi \right] d \phi 
\]

(1)

\[
S_f(Q) = 1 + \frac{2}{N_k} \sum_{k=1}^{N_k} (N-k) \cos(k D Q \cos \phi) \times \exp(-k(Q \cos \phi)^2 \sigma_0^2/2)
\]

(2)

\[
P_c(Q) = f_c(Q)^2
\]

(3)

\[
P_i(Q) = f_i(Q)^2 = \int_0^{\pi/2} \left[ \sin(Q(h + d \cos \phi)/Q \cos \phi) \times \frac{2f_i \sin(Q(R sin \phi)}{Q R sin \phi} \right] ^2 \sin \phi d \phi
\]

(4)

\[
\rho(\text{SLD}) = \sum_n \frac{Z_n}{V_m} \rho_c = 2.81 \times 10^{-13} \text{ cm}
\]

(5)

In these equations, \( R \)=tactoid radius, \( h \)=silicate layer thickness, \( \rho_c \)=silicate layer electron density, \( \rho_p \)=interlayer electron density, \( \Delta \rho_c = \rho_c - \rho_p \), \( \Delta \rho_p = \rho_p - \rho_m \), \( N \)=number of silicate layers in stack, \( d \)=average thickness of surfactant layers, \( D \)=interlayer distance (center-to-center), \( \sigma_o \)=standard deviation of interlayer distance, \( N_{\text{SAMH}} \)=scale factor: number of platelets in unit volume x membrane thickness, \( Z_i \)=atomic number of \( i \)-th atom, \( V_m \)=molecular volume. We classify the structural parameters in Eqs. (1)–(5) into fixed parameters (whose values are pre-calculated and fixed during fitting), global parameters (whose values are fitted but remain the same across all the membrane samples), and sample parameters (whose values are fitted and change from sample to sample). These parameters are listed in Table 1. Specifically, the flake radius \( R \) was set as 10,000 Å as obtained from the TEM analysis (discussed later in this report), and the AMH-3 layer thickness \( h \) is known to be 10 Å [20].
The electron density of AMH-3 layers ρ₂ was calculated as 1.862 × 10⁻⁵ Å⁻² using Eq. (5). The electron density of the interlayer swelling agent ρ₁ and the polymer matrix ρ₂ were fitted globally for all the samples since they are independent of the AMH-3 loading. These parameters were constrained to have maximum values corresponding to the bulk density and composition of the swelling agent and the polymer.

Fig. 4 and Table 2 show the SAXS data and the results of the fitting simulations for SAMH-3/CA composite membranes with 3 different particle loadings (2%, 4%, and 6%). Good fits of the experimental spectra were obtained. Table 2 shows the structural parameters obtained for SAMH-3 stacks in the composite membranes. The average number of stacks of AMH-3 layers in each composite membrane was found to be in the range of N=4-8, thereby demonstrating a high degree of exfoliation of the SAMH-3 particles from the original swollen material. The surfactant layer thickness between AMH-3 layers in the composite membranes was found to be in the range of 12-20 Å. This is about a factor-of-two decrease in comparison to the original 30 Å surfactant layer thickness between AMH-3 layers in the composite membranes. The surfactant layer thickness of SAMH-3 was found to be in the range of 12 Å. 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Specifically, the CO₂ permeability increased by almost 54% and CO₂/CH₄ selectivity has been maintained at the same level as the pure CA membrane. This is a clear demonstration of the ‘nanoporous flake/polymer hybrid membrane’ concept that shows significant improvement on gas permeability while maintaining selectivity.

The enhancement of CO₂ permeation (as shown in Fig. 6a) with only a small loading of porous flakes cannot be explained by conventional permeation models for membranes containing high-aspect-ratio flakes. To illustrate this, the Cussler model [41] (Eq. 6) was applied to fit our experimental data of CO₂/CH₄ gas separation and to estimate the permeability of gases through AMH-3 layers. The Cussler model estimates the flux (J) of a component in a membrane containing porous flakes in relation to the flux (J₀) in a bare membrane:

\[
\frac{J}{J_0} = 1 - \phi + \frac{1}{1 + \frac{\phi}{\alpha^2}} \frac{1}{\delta^2} 
\]

where \( \phi \) is the particle loading, \( \alpha \) is the particle aspect ratio, and \( \delta \) is the ratio of diffusivities of the component in the matrix and the flakes. In the present case, the aspect ratio \( \alpha \approx 30 \) based on TEM analysis, and the only fitting parameter is \( \delta \). Fig. 6b shows our experimental data for CO₂ permeability of composite membranes as a function of flake loading (0, 2, 4, 6%) and the highest possible permeability predicted by the Cussler model (when \( \delta \to 0 \), i.e., CO₂

Table 3

<table>
<thead>
<tr>
<th>CO₂ P (Barrer)</th>
<th>CH₄ P (Barrer)</th>
<th>CO₂/CH₄</th>
<th>CO₂/CH₄</th>
<th>CO₂/CH₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare CA</td>
<td>7.55 ± 0.29</td>
<td>0.26 ± 0.01</td>
<td>29.61 ± 0.29</td>
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</tr>
<tr>
<td>2 wt% SAMH-3</td>
<td>9.65 ± 0.02</td>
<td>0.33 ± 0.01</td>
<td>29.24 ± 0.80</td>
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</tr>
<tr>
<td>4 wt% SAMH-3</td>
<td>10.36 ± 0.25</td>
<td>0.35 ± 0.01</td>
<td>30.03 ± 0.34</td>
<td></td>
</tr>
<tr>
<td>6 wt% SAMH-3</td>
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<td>0.39 ± 0.01</td>
<td>29.71 ± 0.17</td>
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</table>

Fig. 5. TEM images of exfoliated AMH-3 in 6% SAMH-3/CA composite membranes: (a) low-magnification image, (b)-(d) high resolution images to show typical flake thicknesses, and (e) partially exfoliated SAMH-3 flakes. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
diffusion through the filler is infinitely faster than through the polymer. It is seen that the model cannot describe the experimental permeation data from the SAMH-3/CA composite membrane. A similar result was previously predicted by Konduri [42], who calculated the diffusivity of H₂, N₂, and O₂ in the AMH-3/PDMS nanocomposite system by molecular dynamics simulations and showed that the Cussler equation cannot explain the H₂/O₂ and H₂/N₂ selectivities obtained from atomistic simulation. The incorporation of nanoscale flakes in the CA matrix results in a new material with its own characteristic molecular transport properties that cannot necessarily be understood as a combination of the bulk properties of the two constituent materials.

Fig. 7 illustrates possible mechanisms that explain the gas permeation enhancement in this system. Based on SAXS/TEM analysis, the exfoliated AMH-3 is stacked in flakes of 4-8 layers, with interlayer spaces of size ~2 nm containing the swelling agent. The molecular sieving effect and high aspect ratio (~30) of the exfoliated AMH-3 tactoids may increase the CO₂ permeability and the CO₂/CH₄ selectivity [23,24,43]. At the same time, transport through the mesopores that are known to exist in the interlayer spaces [25], may also result in enhanced gas permeability for both CO₂ and CH₄. In a limiting case, transport through the interlayer spaces could be governed by Knudsen diffusion, wherein CH₄ is transported ~1.7 times faster than CO₂. This may tend to lower the overall CO₂/CH₄ selectivity in the composite membrane. This complex transport mechanism operating within the SAMH-3 flakes can also be interpreted as increasing the effective volume fraction of the inorganic material. It is of future interest to control the permeability and selectivity of the interlayer spaces, by further increasing the degree of exfoliation of the AMH-3 layers or introducing other materials (e.g., silica or polymers) to substitute the swelling agent in the mesoporous interlayer spaces.

In comparison to composite membranes using isotropic molecular sieve particles that conventionally require incorporation of up to 50 wt% of molecular sieve particles [10], the enhancement of separation performance using small quantities of nanoporous layered oxides such as SAMH-3 may find important applications in reducing the required membrane area, as well as avoiding problems associated with high particle loadings such as agglomeration, leaky interfaces, and loss of mechanical strength.

The above proposed mechanism does not include the effects of possible changes in the polymer packing [44] caused by incorporation of the AMH-3 flakes, although these effects may be small for the low flake loadings. As mentioned earlier, the fitted electron density of the CA matrix in the SAXS analysis indicates a possible lowering of the CA matrix density. This may have the effect of increasing the permeability of the CA matrix (i.e., the value of J₀ in the Cussler equation could increase with AMH-3 loading). The maintenance of CO₂/CH₄ selectivity in such a situation could be explained as being due to a competing effect of the SAMH-3 flakes (which increase the selectivity) and the expanded CA matrix (which lowers the selectivity). More detailed characterization of the CA matrix phase is required to validate this hypothesis.

4. Conclusions

SAMH-3/Cellulose Acetate (CA) nanocomposite membranes were fabricated with the use of a high-shear mixer, and the microstructure and properties of the resulting membranes was investigated by a range of experimental techniques. From our detailed SAXS study, the number of SAMH-3 layers in an exfoliated stack are found to be 4-8, in good agreement with the SAMH-3 flake thickness measured by TEM. The SAMH-3/CA composite membranes were investigated for their CO₂ and CH₄ gas permeation characteristics. Significant improvements in mixed-gas separation performance were attained with only 2–6 wt% of AMH-3 loading. This effect cannot be predicted by conventional models, and indicates a complex combination of transport phenomena occurring in such membrane systems. Such transport phenomena include competing effects of transport through the SAMH-3 pores, the interlayer spaces, and potentially through a
lower-density CA matrix phase. The present approach could be practically useful in mitigating effects of particle aggregation and poor polymer-particle adhesion encountered in fabricating com-posite membranes with higher volume fractions of inorganic materials.

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References