Preparation and properties investigation of PMMA/silica composites derived from silicic acid

H. P. Fu, R. Y. Hong, Y. J. Zhang, H. Z. Li, B. Xu, Y. Zheng and D. G. Wei

Hybrid materials based on silicic acid and polymethyl methacrylate (PMMA) were prepared by in situ bulk polymerization of a silicic acid sol and MMA mixture. Silicic acid sol was obtained by tetrahydrofuran (THF) extraction of silicic acid from water. Silicic acid was prepared by hydrolysis and condensation of sodium silicate in the presence of 3.6 M HCl. As a comparative study, PMMA composites filled by silica particles, which were derived from calcining the silicic acid gel, were prepared by a comparable in situ polymerization. Each set of PMMA/silica composites was subjected to thermal and mechanical studies. Residual THF in PMMA/silicic acid composites impacted the properties of the polymer composites. With increase in silica content, the PMMA composites filled with silica particles showed improved thermal and mechanical properties, whereas a decrease in thermal stability and mechanical strength was found for PMMA composites filled with silicic acid dissolved in THF. With a better compatibility with polymer matrix, silicic acid sol shows better reinforcement than silica particles in PMMA films prepared via blending of the corresponding THF solutions. Copyright © 2008 John Wiley & Sons, Ltd.

Keywords: silica; silicic acid; PMMA; composite; mechanical properties

INTRODUCTION

In recent years, the synthesis and application of nanocomposites had attracted much attention because of their excellent properties. As a functional-filling material, silica nanoparticles are widely used in many fields due to the reinforcement to the matrix. Various methods have been reported for preparing silica materials such as plasma synthesis, chemical vapor deposition, sol–gel processing, microemulsion preparation, gas combustion synthesis, and hydrothermal technique. Among these methods, the sol–gel processing is an attractive approach owing to its controllable process and narrow size distribution of the obtained silica nanoparticles.

Recently, nanocomposites consisting of polymers and nanoparticles are used increasingly in various extreme working conditions for the high performance of these materials. Researches are going on for the reinforcing thermoplastic or thermosetting polymers with organic or inorganic nanoparticles. Karatas et al. studied the influence of silica on polyimide via a combination of sol–gel and thermal imidization techniques. The results showed that the thermal stability and mechanical strength of the polyimide reinforced with 5–10 wt% of silica are better than those of pure polyimide. Tanahashi et al. pointed out that the application of nanosized fillers demonstrated the potential to improve the general performance of thermoplastic polymers fundamentally. It has been shown that a considerable improvement of mechanical properties can be achieved by adding a low volume content of nanosized fillers, somewhere in the range of 1–5 vol%.[16–18] This is very important due to the high cost of nanosized fillers.

However, when nanoparticles are used as fillers to prepare polymer nanocomposites, a homogeneous dispersion in the matrix is required. As the particles tend to aggregate, special techniques have to be developed to achieve a homogeneous dispersion. One solution is mechanical mixing using high shear forces for dis-aggregation whereas another technique is ultrasonic irradiation. Chemical methods can also be used, such as sol–gel processing or surface modification of nanoparticles to increase the compatibility between nanoparti-
cules and organic phase. Nanosized fillers acting as a part of the microstructure and the interfacial interactions mainly control the properties of the materials. This opens a new way to prepare high-performance polymeric materials.

Blended with silica nanoparticles, polymethyl methacrylate (PMMA) can be improved remarkably in mechanical and thermal properties. Yang et al. investigated the mechanical properties of silica reinforced PMMA films prepared by solution polymerization, and the results showed that the mechanical properties had an significant increase over pure PMMA. In the present investigation, silicic acid sol was first prepared using sodium silicate and hydrochloric acid, and then silica particles were obtained by a sol–gel route based on silicic acid sol. To study the influence of silica on the performance of PMMA slices, the silica filled PMMA composites were prepared by in situ bulk polymerization after mixing either silicic acid sol or silica particles with MMA monomer. Afterwards, the thermal and mechanical properties of the resulting PMMA composites were characterized. The properties of silica filled PMMA films obtained via solution blending were also investigated.

EXPERIMENTAL

Materials

Methyl methacrylate (MMA) of chemical grade (at a purity of 99.9%) was distilled under reduced pressure prior to use. Azo-bis-isobutyronitrile (AIBN), which was used as an initiator, was recrystallized in ethanol. The PMMA, which was used to prepare thin films, was obtained from Anli Chemical Works, Suzhou, China. Sodium silicate (Na$_2$O·SiO$_2$·9H$_2$O), hydrochloric acid, tetrahydrofuran (THF), sodium chloride (NaCl), absolute sodium sulfate (Na$_2$SO$_4$), and other materials were all analytical grade. Deionized water was used throughout the experiments.

Preparation

Preparation of silicic acid sol

Hydrochloric acid (100 ml, 3.6 M) was added to a three-necked round-bottomed flask, which was cooled by ice water. Then 100 ml of 1.2 M Na$_2$O·SiO$_2$ solution was added into the flask dropwise using a dropping funnel under mechanical stirring. The reaction was continued for another 2 hr at 5°C after the sodium silicate solution was added. Thereafter, NaCl solid was added to saturate the solution. 100 ml of THF was added and the solution was vigorously stirred for 2 hr to facilitate the extraction of silicic acid by THF. After achieving extraction equilibrium, the organic phase was isolated using a separatory funnel. The organic phase was dried over anhydrous Na$_2$SO$_4$. Finally, the silicic acid sol was obtained after removing the Na$_2$SO$_4$ by filtration.

The silica content in such sol (g ml$^{-1}$) was measured as follows: 10 ml of sol was heated at 100°C for 2 hr, and the obtained powder was weighed. The silica content was calculated by the powder weight dividing the total volume of silicic acid sol.

Preparation of silica particles

A silicic acid gel was obtained after the silicic acid sol was stored at room temperature for several days. The gel was crushed into powder and washed with deionized water and ethanol for five times, respectively, and then dried in vacuum for 12 hr at room temperature. The white powder was ground using a high-energy ball milling machine operating at 40 rpm for 2 hr. The resultant particles were heated at 100°C for 1 hr to remove any physically absorbed water and residual THF, and then calcined at 400°C for 2 hr to yield silica particles.

Preparation of silica filled PMMA composites

Preparation of PMMA slices

The silica filled PMMA composites were prepared by in situ bulk polymerization. In a typical run: silica particles (0.2 g) were dispersed into MMA (21 ml) through ultrasonic irradiation for 1 hr, and then mixed in a high-energy ball milling machine operating at 40 rpm for 2 hr. Then AIBN (0.1 wt% of MMA) was added. The polymerization reaction was performed at 80 ± 2°C under magnetic stirring for about 20 min until the conversion of MMA was about 12–15%. Then, the suspension was poured into a stainless steel mold, which was coated with a thin film of Garry Mould Release Agent (non-paintable). The aperture at the top of the mold was wrapped with a plastic foil. Thereafter, the mold containing the prepolymer and silica particles was kept at 40°C for 24 hr, and solidification took place. Then, the temperature was adjusted to 100°C and kept for 1 hr to facilitate the polymerization of the MMA monomer. Finally, PMMA slices (Sample A$_x$) with prescribed silica content were obtained by disassembling the molds.

PMMA slices filled by silicic acid sol were prepared similarly to the above procedures, except that silicic acid sol instead of silica particles was dispersed into MMA and after mold filling, the mold was subjected to reduced pressure (0.5 atm) for 30 min to eliminate THF. Those samples are named as Sample B$_x$.

The subscript $x$ (0.5, 1, 1.5) in Sample A$_x$ and Sample B$_x$ denotes the theoretic content of silica particles in PMMA, that is, the $x$ values mean the feed amount of silica in experiments which is fixed at 0.5, 1, and 1.5 wt%, respectively. The actual silica content in these samples was obtained by TGA.

Preparation of PMMA films

PMMA films filled by silica were obtained as follows: PMMA (2 g) was first dissolved in THF (20 ml) at room temperature, and an appropriate amount of silica particles or silicic acid sol was added into the solution and dispersed using a high-energy ball milling machine operating at 40 rpm for 2 hr. The content of silica in PMMA was fixed at 2 wt%. As for the silicic acid sol filled PMMA films, the silica content was adjusted by the volume of silicic acid sol. Finally, the suspension was spread onto a glass plate using a wet film applicator (SZQ-100, XD Env. Eng. Tech. Inc., Shanghai, China). The applicator was driven by an automatic film dauber (AFA-II, XD Env. Eng. Tech. Inc., Shanghai, China) to obtain films with precise thickness. Afterwards, the wet films were dried at room temperature for one day. Finally, the dried films were removed from the glass plates to yield different PMMA films with a thickness of about 15 μm as measured using a thickness gage (No. 7327, Mitutoyo Corp., Japan).

Characterization

Measurements

The crystalline phases were identified by X-ray powder diffraction (XRD) with a D/Max-III C, using Cu-κ radiation. The size and shape of silica particles were determined using a transmission electron microscope (TEM, H-600-II, Hitachi, Japan). The particle
size distribution (PSD) was measured using a Malvern HPPS5001 laser particle-size analyzer. The content of NaCl in the samples was measured by an atomic absorption spectrophotometer (AAS, 180–80, Hitachi, Japan).

The purity of obtained silica particles was measured as follows: 0.5 g of silica particles were dispersed in deionized water with stirring for 30 min and the washed solution was collected. The particles were extracted three times so that the dissolvable substances were totally dissolved in water. The washed solutions were put together and the sodium ion content in the solution was measured by AAS. For silicic acid sol, 5 g of sol was first heated at 100 °C for 2 hr, then the powders obtained were subjected to the same procedure mentioned above and the content of sodium ion was measured.

The ultraviolet–visible (UV–Vis) absorption of different kinds of PMMA slices was measured using a U-2810 spectrophotometer (Hitachi, Japan). The thermal behavior and silica content in PMMA/silica composites were measured by thermogravimetric analysis (TGA, SDT-2960, TA, America). The glass transition temperature (T_g) was obtained using a differential scanning calorimeter (DSC, DSC2010, TA, America). A Hitachi S-4700 scanning electron microscope (SEM) was used to study the morphology of the PMMA/silica composites. A scanning surface was obtained by fracturing samples at liquid nitrogen temperature followed by coating the cross section with gold.

**Mechanical properties of PMMA**

The hardness test for PMMA slices was performed according to the China National Standard JB/T 6148–1992[24] using a LX-D plastic durometer (Shore-type durometer, Qianzhou testing Inst. Co. Ltd., Wuxi, China) at room temperature. Measurements were performed five times for each sample and the mean value was calculated.

To obtain the impact strength of different kinds of PMMA slices, an Izod impact machine tester with digital display (JBL-22, Shenzhen KQL Testing Instruments Co., Ltd) was used according to GB/T 1843–1996[25]. Unnotched specimens with rectangular dimensions of 80 × 10 × 4 mm³ were fractured by the impact energy of 5.5 J with an impact speed of 3.5 m s⁻¹ at room temperature. The distance between the impact point and fixed point was set to 22 mm.

Flexural test for PMMA slices was performed according to GB/T 9341–2000[26] using a universal testing machine (WDT20, Shenzhen KQL Testing Instruments Co., Ltd) in a three-point bending configuration at room temperature. A PC was connected to the testing machine, and the crosshead speed was set to be 2 mm min⁻¹. The force transducer with a precision of ±0.02% was made by Transcell Tech. Inc. USA.

The tensile test for PMMA films was carried out according to GB/T 13022–1991[27] at room temperature. The crosshead speed was set to be 2 mm min⁻¹.

The GB standards were established according to the ISO ones.

**RESULTS AND DISCUSSION**

**XRD patterns**

The XRD pattern of silica particles calcined at 400 °C is shown as curve (a) in Fig. 1. It can be seen that there is only one diffraction peak at around 2θ = 23°, which can be indexed to the amorphous phase of silica. The XRD patterns of PMMA filled either by silica particles or silicic acid sol are similar to that of pure PMMA. The characteristic peak of silica particles around 23° is not shown in curve (c) and (d). This may be due to the fact that the diffraction peak of silica is weak and covered by the peak of PMMA.

**Transmission electron microscopy**

Figure 2(a) shows the TEM image of silicic acid sol. The content of silica in such sol is calculated to be 0.148 g ml⁻¹. The TEM image shows that there are aggregates of silica particles in the sol, and the shape is irregular. As there are hydroxyl groups in the silicic acid, a dehydration reaction of some silicic acid took place, and polysilicic acid was formed in the sol, so the silica particles are connected with each other.

The size and shape of silica particle after heat treatment is revealed by TEM image, as shown in Figure 2(b). The result shows that the normal size of silica particles is around 130 nm, larger than that of silica particles existing in silicic acid sol. As the silicic acid sol transformed to gel during the sol–gel processing and then calcined at 400 °C, the particles became bigger. We can also see that the shape of silica particles is spherical, and the size distribution of silica particles is uniform, which is also proved by the results discussed in the Size and purity of silica section.

**Size and purity of silica**

The properties of nanosized materials depend strongly on the particle size and PSD. The aggregation of nanoparticles might depress some excellent performances of nanomaterials. The PSD of silica particles is shown in Fig. 3, which indicates that the obtained silica particles have a narrow PSD and the size of most silica particles is about 134 nm.

As the reagents used in the experiment were all of analytical grade, the only ions in the system are chlorine and sodium, thus, the impurities in the system can only be residual NaCl. Therefore, the purity of silicic acid sol or silica particles can be calculated through the content of soluble NaCl in the product. The results of AAS show that the concentration of sodium ion in the washed solution with respect to silicic acid sol and silica particle is 7.50 and 0.469 mg L⁻¹, respectively, and the relevant weight of NaCl in 5 g sol and 0.5 g silica particles is calculated to be 4.77 × 10⁻³ g.
and $5.96 \times 10^{-5}$ g, respectively. That is, the content of NaCl in silicic acid sol is 0.0954 wt%, which is much lower than the silica content (about 14.5 wt%). The purity of silica particles is calculated to be 99.988%.

**TGA**

The TGA results of different silica filled PMMA slices are shown in Fig. 4. The PMMA is assumed to be totally burnt out at 500°C, and the residue can only be the added silica. The illustration in Fig. 4 indicates that the silica content in Sample A is basically equal to the feed amount of silica particles, whereas owing to the evaporation of MMA in vacuum processing, the silica content in Sample B is slightly higher than the amount of silica added.

Inorganic fillers play an important role in the thermal stability of polymeric nanocomposites through interfacial interaction. Table 1 shows the thermal stability of PMMA/silica composites. With the increasing silica content, an increase in thermal decomposition temperature was found for Sample A, however, a decrease was found for Sample B. Note that at 10% weight loss, a 26.2°C increase for Sample $A_{1.5}$ and 20°C for Sample $B_{0.5}$ are observed. These provide strong evidence that strong interfacial interactions between PMMA and the filled silica are achieved. Moreover, better interfacial interaction between silica additives and polymer chain introduced by the deeper penetration of small particles in the polymer matrix also enhances the thermal stability of composites throughout the degradation process, as indicated by the decomposition temperature of PMMA with the 50% weight loss in Table 1, which is the major thermal failure temperature for polymer composites.

**DSC analysis**

The DSC results of pure and silica filled PMMA slices are shown in Fig. 5. The glass transition temperature ($T_g$) of PMMA is improved after filling by silica particles. The $T_g$ of pure PMMA is 106.42°C, whereas the $T_g$ is enhanced to 108.16 and 108.59°C for Sample $A_{0.5}$ and Sample $B_{0.5}$, respectively. Different trends of $T_g$ for Sample $A$ and Sample $B$ were observed with the increasing silica content in PMMA composites, as shown in Fig. 5.

For Sample A, the $T_g$ increased along with the increasing silica particles content in PMMA, as shown in Fig. 5(a). As silica particles were added during the in situ polymerization, strong physical bonds formed between silica particles and macromolecule network, and the movement of polymer chains at high temperature was restrained. As more silica particles added, more physical bonds formed and further restricted the move-
ment of macromolecule chains. However, as more silica particles were being added in PMMA, the transparency of the sample was lowered. So the content of fillers in PMMA was best to be 1–2 wt%. For Sample B, Sample B0.5 has the highest $T_g$, and then $T_g$ decreased with the increasing silica content, as shown in Fig. 5(b). More silicic acid sol should be added with higher silica content in PMMA. Therefore, the THF content was increased in the polymerization mixture. Though the prepolymer was held under reduced pressure to eliminate most of the THF solvent before low-temperature solidification, the residual THF could influence the polymerization process and reduce the molecular weight of PMMA, leading to a decrease in the $T_g$.

Morphology of PMMA/silica composites

The SEM images of the fracture surface of PMMA slices filled with silica particles or silicic acid sol are shown in Fig. 6. The result indicates that the inorganic silica particles (denoted by black arrowheads) show a homogeneous dispersion and most of the small particles are deeply penetrated in PMMA matrix. Some small pin-holes (denoted by white arrowheads) which are caused by the residual THF in the PMMA can also be found for Sample B1.5. The SEM image for Sample A1.5 shows a good dispersion in PMMA of silica particles and no aggregates of silica particles were observed, as shown in Fig. 6(b). The well-dispersed silica nanoparticles ensure the better thermal and mechanical properties of the reinforced polymer.

UV–Vis analysis

The UV–Vis spectra of PMMA composites are shown in Fig. 7. Compared with pure PMMA, the transparency of silica particles or

![Figure 4. TG curves of different PMMA slices (a)–(c) silica particles reinforced PMMA; (d)–(f) silicic acid sol reinforced PMMA.](image)

![Table 1. Thermal stability of silica filled PMMA composites](table)

<table>
<thead>
<tr>
<th>Sample</th>
<th>10% Weight loss</th>
<th>50% Weight loss</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$T_g$ (°C)</td>
<td>$\Delta T_g$ (°C)</td>
</tr>
<tr>
<td>PMMA</td>
<td>228.4</td>
<td>—</td>
</tr>
<tr>
<td>Sample A0.5</td>
<td>234.3</td>
<td>5.9</td>
</tr>
<tr>
<td>Sample A1</td>
<td>249.2</td>
<td>20.8</td>
</tr>
<tr>
<td>Sample A1.5</td>
<td>254.6</td>
<td>26.2</td>
</tr>
<tr>
<td>Sample B0.5</td>
<td>248.4</td>
<td>20</td>
</tr>
<tr>
<td>Sample B1</td>
<td>243.6</td>
<td>15.2</td>
</tr>
<tr>
<td>Sample B1.5</td>
<td>240.1</td>
<td>11.7</td>
</tr>
</tbody>
</table>

![Figure 5. $T_g$ of different PMMA slices.](image)

![Figure 6. SEM images of Sample B1.5 (a) and Sample A1.5 (b).](image)
The transparency of Sample A or Sample B is further decreased with the increasing content of silica. Since the wavelength of the incidence ray is of the same magnitude of the silica particle size, and the silica particles have strong reflectivity against the incidence ray, and even though the samples have been ultrasonically irradiated and ball milled, the well-dispersed silica particles also have scattering effect. Both of them result in the decrease of the transparency of all samples. Compared with Sample A, Sample B has higher transparency, which is due to the better compatibility of silicic acid sol than that of silica particles in PMMA composites.

### Mechanical properties

#### Apparent hardness

The apparent hardness of PMMA composite is listed in Table 2. After blending with silica, the apparent hardness of PMMA slices is enhanced. Due to the large surface area and high surface energy, the silica particles can be adsorbed among PMMA chains via physical bonding and act as restriction sites for the movement of polymer chains. For Sample A, the number of restriction sites is increased with the increasing silica content and the reinforcement effect is much more obvious. The hardness of Sample B shows a decrease as the silica content increases. A similar result is observed for impact strength as discussed in the impact strength section. The residual THF in PMMA which increases with the increasing silica content can affect the structure of the composites. This may be a reason for declining hardness as the silica content increases.

#### Impact strength

The impact strength of PMMA slices is shown in Fig. 8. For Sample A, the filling of silica particles obviously improves the impact strength of PMMA slices. The impact strength of PMMA composites increases with the increasing silica content, which can be due to the more reinforcement sites formed among the polymer chains. It suggests the importance of incorporating the silica particles to improve the mechanical properties of PMMA slices. Considering the strong increase in impact strength of PMMA composites again, it is obvious that some energy is eliminated by the filled silica particles during the breaking-down process.

As for Sample B, the impact strength is enhanced at low content of silica ($x = 0.5$) and then weakened at high content ($x = 1 \text{ or } 1.5$). With the increasing silica content, more THF is remained in the polymer composites and thereafter induces the formation of small pin-holes in PMMA during the heat treatment at 100$^\circ$C (as shown in Fig. 6(a)). During the test of impact strength, such pin-holes become the weak points and the PMMA slices are easy to be broken under an abrupt impact and the impact strength decreases.

#### Flexural strength

The effect of particulate fillers on the stress-strain behavior of polymeric materials can be much different due to the interaction between the particles and polymer. The flexural strength measured for different PMMA composites is shown in Fig. 9. It can be concluded that as the silica content increases, the flexural strength of PMMA slices either filled by silica particles or by silicic acid sol increases. The reinforcement mechanism of polymer by silica can be explained as this: as the active surface of silica particles connected with some long polymer chains and the physical bonding between silica and polymer chains are formed, the flexural stress could be transferred through the inorganic linking point to the other polymer chains. When one chain gets ruptured under external stresses, the others can still support the...
polymer structure. So the whole specimen is not threatened by the stresses, and the flexural strength enhances.

For the Sample A, as the content of silica particles increased, the number of coupling points between PMMA and silica particles also increased; therefore, the flexural strength is improved. As for Sample B, contrary to the impact strength, the flexural strength is enhanced with the addition of more silicic acid sol, though there maybe small pin-holes existing in the composites. There are two factors influencing the flexural strength of PMMA composites: the addition of silica and the existence of pin-holes in the structure. During the test, stress was imposed slowly on the samples, though the pin-holes might lower the flexural strength; however, such influence was negligible. On the contrary, the silica well dispersed in PMMA composites has an obvious enhancement to the flexural strength. As a result of the two opposite effects, the flexural strength of silicic acid sol filled PMMA slices is improved.

Tensile properties of PMMA films

In the Mechanical properties section we found that the mechanical properties (hardness and impact strength) of silicic acid sol filled PMMA had a falling trend as the silica content increased, which could be ascribed to the residual THF in PMMA. To eliminate the influence of the residual THF on the filled materials, we investigated the properties of PMMA films prepared through solution blending as described in the Preparation of PMMA films section. As the PMMA is dissolved by THF during preparation, the THF existing in silicic acid sol does not influence the properties of PMMA films.

The stress–strain curves of pure PMMA and silica filled PMMA films are presented in Fig. 10. The curve patterns are affected by the filling of either silica particles or silicic acid sol. The results show that the addition of silica increases the tensile strength due to the strong interfacial interaction between silica and PMMA films.

Table 3 shows the tensile strength and tensile modulus of various silica filled PMMA films. The tensile strength and tensile modulus of the films increase after filling with silica and the elongation to break decreases. Such a phenomenon is attributed to the high resistance exerted by rigid silica particles against the plastic deformation as well as the stretching resistance of the polymer chains surrounded by silica particles. From Table 3, we can also conclude that the silicic acid sol filled PMMA films have the best tensile properties. As the silicic acid sol is more compatible with PMMA than silica particles, and the properties of PMMA films are not affected by the residual THF, so the filler reinforcement effect is more obvious. Such results confirmed the argument that the residual THF in PMMA slices has a deteriorative effect on the polymer composites.

CONCLUSIONS

Silica particles with a size of 134 nm and with a narrow size distribution were prepared by sol–gel processing. The PMMA slices filled by two kinds of silica were obtained by in situ bulk polymerization. The glass transition temperature (Tg) as well as the mechanical properties of silica particles reinforced PMMA slices increased with the increase in silica content. In contrast, the Tg and apparent hardness as well as the impact strength of silicic acid sol filled PMMA slices were reduced, whereas the flexural strength was enhanced with the increase in silica content. The PMMA films reinforced by silicic acid sol have the best tensile properties among all films. The dispersion of silica particles in a polymer matrix has significant impact on the polymer mechanical properties. Silicic acid sol which shows better compatibility with the polymer matrix may replace silica particles to reinforce the polymer matrix. This opens a new way to prepare high-

Table 3. Effect of silica on the properties of PMMA films (the silica content was fixed at 2 wt%)

<table>
<thead>
<tr>
<th>Samples</th>
<th>Elongation at break (mm)</th>
<th>Modulus (MPa)</th>
<th>Tensile strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMMA</td>
<td>4.87</td>
<td>525.61</td>
<td>12.68</td>
</tr>
<tr>
<td>Silica particles + PMMA</td>
<td>1.61</td>
<td>566.98</td>
<td>17.58</td>
</tr>
<tr>
<td>Silicic acid sol + PMMA</td>
<td>1.89</td>
<td>570.41</td>
<td>20.08</td>
</tr>
</tbody>
</table>
performance polymeric materials. However, the residual THF in the polymer matrix should be as low as possible in actual applications.

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