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### **Preparation and Properties of Epoxy Nanocomposites**

# Part 2: The Effect of Dispersion and Intercalation/Exfoliation of Organoclay on Mechanical Properties

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#### ABSTRACT

The effect of the dispersion and intercalation/exfoliation of organoclay on the mechanical properties of epoxy nanocomposites was studied. The epoxy resin was EPON828 and the hardener was Jeffamine D-230, an amine-terminated polyoxypropylene diol. The organoclay Cloisite 30B (montmorillonite treated with a quaternary ammonium intercalant) was used. Nanocomposites were prepared by different mixing devices that can generate different shear forces, such as a mechanical stirrer, a microfluidizer, and a homogenizer. The tensile and compressive properties of the epoxy resin and its epoxy nanocomposites (ENCs) were determined. The effects of nanoclay on the mechanical properties of the EPON828-D230 system were also investigated by dynamic mechanic analysis (DMA). The results indicate that the modulus increases almost linearly with the clay loading and also is improved with the quality of micro-dispersion, although the latter plays a less important role. On the other hand only good dispersion can improve the strength, while poor dispersion results in loss of strength. The strength levels off above 4 wt% organoclay loading. It can be concluded that finer and more uniform dispersion increases the clay surface area available for interaction with the matrix and reduces stress concentration in the large aggregates that initiate the failure under stress. It is also observed that the presence of nanoclay C30B does not significantly affect the  $T_g$  of the epoxy systems regardless of the level of clay dispersion and clay loading. DMA results also show the positive effect of dispersion and intercalation/exfoliation on the storage modulus of ENCs.

Key words: dispersion, nanoclay, epoxy, nanocomposites, mechanical properties.

#### **INTRODUCTION**

Processing parameters have a large influence on the dispersion of clay in polymer. This in turn has an effect on the physical and mechanical properties of nanocomposites. The clay nanolayers are more effective in improving mechanical properties when the polymer is in its rubbery state than in its glassy state. Lan et al [1] mixed the organoclay  $CH_3(CH_2)_{17}NH_3^+$ -MMT into mixtures of epoxy and amine at 75°C and stirred for 30 minutes. With 7.5 vol% of the organoclay, the strength of an elastomeric polymer matrix  $(T_g \sim -40^{\circ}\text{C})$  was improved by more than 10-fold but no significant improvement was found for glassy epoxy. However, it is not clear whether this effect is solely related to the physical state of the epoxy system or also to the difference in chemistry of the matrix and the quality of dispersion of the two systems. The behavior of glassy epoxy-clay nanocomposites in compression was studied by Massam and Pinnavaia [2]. The compressive yield strength and the modulus of the exfoliated nanocomposites were increased by 17 and 27%, respectively, with a clay loading of 10 wt%. However the conventional composites were completely ineffective in providing reinforcement to the matrix. They also found that interfacial interactions, platelet aspect ratios, and layer charge densities also have a direct impact on the compression behaviour of the nanocomposites. The dimensional stability, thermal stability and solvent resistance of the glassy matrix can also be improved when the clay nanolayers are present. Researchers from Nanocor [3] showed that the flexural modulus of amine-cured epoxy nanocomposites increased 40% for a high- $T_g$  system (glassy system) at 8 wt% clay, but the strength did not. Zilg et al. [4] confirmed that the tensile strength properties of nanocomposites did not improve but rather decreased depending on the type of alkylamine intercalant. Organoclays (alkylamine-treated fluorohectorites) were dispersed in DGEBA (Araldit CY225) at 80°C and 13 mbar pressure. The tensile strength decreased 17% with 10 wt% butylamine-treated clay and it decreased 39.5% with 10 wt% octadecylamine-treated clay. This can be explained by the poor interfacial interaction between the epoxy matrix and the organoclay. Kornmann et al. [5] showed that with octadecylamine-treated MMT, the flexural modulus increases by more than 40% for the EPON 828/Jeffamine D230 system with 10wt% clay and by 28% for the EPON 828/3DCM system with 8 wt% clay. However, no increase in flexural strength was reported. Yasmin et al. [6] used a three-roll mill to disperse the clay nanoparticles in an epoxy matrix and improved the distribution of the particles. Chen and Tolle [7] achieved fully exfoliated layer silicate epoxies by high-shear mixing in the presence of acetone. However, the large amount of solvent required meant that considerable time was required for removing it. There is still work to be done to develop nanocomposites with fine dispersions and well-exfoliated morphologies. Oh et al [8] examined the effect of shear forces (by changing the speed up to 1000 rpm with mechanical mixer) on the microstructure and mechanical properties of Epoxy-Clay nanocomposites, the authors reported good increases in modulus for low clay loadings. This paper does not show the results for the strength of the epoxy nanocomposite prepared with 1000 rpm mixer. They only shown the stress-strain curves of the hand mixing method and there is a loss in the stress. From there, the authors speculated that there is still missing either shear or thermodynamic to produce a high degree of dispersion of clay in epoxy. Achieving such well intercalated/exfoliated morphologies with epoxy-based nanocomposites is a challenge, since high shear is always required but epoxy resin typically has rather low

viscosity. From the results of our previous study in which well-dispersed and wellintercalated/exfoliated ENCs were obtained with a non-solvent-assistance method [9]. In this study, the exploration of a different way to generate the shear in order to improve the quality of dispersion, intercalation/exfoliation of clay in epoxy was studied. We used different devices to generate the shear including conventional mechanical mixer, high pressure mixer [10, 11, 12] and especially the high speed mixer which can control the speed up to 24000 rpm. From there we obtained small well-dispersed tactoids with high surface area in the epoxy matrix. The present paper continues our previous one with an exploration of the effect of shear on the dispersion, intercalation/exfoliation of organoclay, and enhance on the mechanical properties of epoxy nanocomposites.

#### EXPERIMENTAL

The epoxy resin used was the standard DGEBA (diglycidyl ether of bisphenol A) resin EPON<sup>TM</sup> Resin 828 from Resolution Performance Products (Houston, TX, USA). This was cured with the polyoxypropylene diamine hardener Jeffamine<sup>®</sup> D-230 from Huntsman LLC (The Woodlands, TX, USA) at a level of 32 phr. The organoclay used was Cloisite<sup>®</sup> 30B from Southern Clay Products, Inc. (Gonzalez, TX, USA). It was dispersed in the epoxy resin at a level of 2.69, 5.50, and 8.43 phr, which leads to a loading of 2, 4, and 6 % by weight after addition of hardener and curing. This nanoclay consists of montmorillonite treated with methyl tallow bis-2-hydroxyethyl quaternary ammonium intercalant. It is widely used in epoxy resins because the 2-hydroxyethyl groups provide improved chemical compatibility with the relatively polar epoxy resin.

The epoxy system and its nanocomposites were cured at 120°C for 2 hours, with subsequent post-cure at 140°C for 2 hours.

Epoxy and clay were pre-mixed together by means of different devices. Samples specifications are shown in Table 1 (Results from X-ray diffraction (XRD) and field emission gun scanning electron microscopy (FEGSEM)). The first one was a "room temperature without mechanical shear" process (Rm), in which the clay and epoxy were stirred at room temperature by hand at about 100 rpm for a few minutes then kept at room temperature for 1 hour. The second one was a "high temperature without shear" process (Tm), in which the clay and epoxy were stirred at 120°C by hand at about 100 rpm for a few minutes then kept in an oven at 120°C for 1 hour. The third method was a "high temperature with low-speed mixing" process (TM), in which the clay and epoxy were stirred at 120°C for 1 hour by a mechanical stirrer at 1000 rpm. The fourth one was a "room temperature and high-speed mixing" process (RS), in which the clay and epoxy were stirred at room temperature by a homogenizer at high speed (24000 rpm) for 1 h. The fifth method was a "high temperature and high-speed mixing" process (TS), in which the clay and epoxy were stirred at 120°C by a homogenizer at high speed (24000 rpm) for 1 h. The sixth one was a high-pressure process (HP), in which organoclay was first dispersed in acetone (at a level of about 8%) with a microfluidizer ( $\approx 15000$  psi or 103 MPa) to form a suspension, and then the suspension was added into the epoxy resins according to the approach used by Liu et al. [10-12]. The desired amount of paste of organoclay and acetone was added to epoxy resin and then the mixture was stirred by hand at room temperature. When the epoxy was visibly dispersed, the mixture was mechanically stirred at 1000 rpm in a fume hood at room temperature for 30 minutes,

followed by slow heating to 80°C for 1 hour. Finally, the mixture was degassed under vacuum at 95°C for 30 minutes. For curing, the required amount of hardener was mixed with epoxy or epoxy-clay mixtures at room temperature for 5 min then subjected to vacuum. Samples were cured at 120°C for 2 hours, with subsequent post cure at 140°C for 2 hours.

The tensile and compression properties of the epoxy system with and without clay were determined at room temperature and 50% relative humidity according to ASTM D638-2002 and ASTM D695-2002 on an Instron 5500R machine, with crosshead speeds of 5 mm/min and 1.3 mm/min, respectively. The DMA results were obtained on a Du Pont 983 DMA (TA instruments) at a constant frequency of 1 Hz, and the amplitude was 0.2 mm. The samples were analyzed from 30°C to 160°C at a heating rate of 2°C/min.

#### RESULTS

The results of the dispersion, intercalation/exfoliation of clay C30B in EPON828-D230 which prepared by different pre-mixing methods are shown in Table 2. This result was summarized from our previous study [9]. The first peak's position ( $d_{001}$ ) in the XRD curves of the ENCs is given in the second column of Table 2. In all the nanocomposite samples, the clay layer separation (degree of intercalation) is considerably higher than in the original C30B where clay gallery distance is about 1.85 nm. This can be concluded that clays have been further intercalated by the epoxy matrix. The results also show that the intensity and the peak position of the epoxy nanocomposites are different depending on the pre-mixing methods. According to the intensity and the position of the XRD peaks, the orders of intercalation/exfoliation can be ranged as the order TS > RS, TM >

Tm > Rm, TS > TM > Tm and RS > Rm. In addition, the average size of the clay particles in the epoxy matrix was also calculate from the FEGSEM and summarized in the third column of the Table 2. The result again confirms that the micro dispersion of ENC made by different pre-mixing methods follows the order TS > HP > RS > TM > Tm> Rm.

The tensile properties of EPON828-D230 with 2 wt% C30B prepared by means of different pre-mixing methods are shown in Figure 1. The presence of clay results in an improvement in modulus for all cases of pre-mixing (Figure 1a). Other researchers have also reported that addition of clay (from 5 wt% and above) increases modulus [1, 13]. However, this study demonstrates that even with a relatively small amount of clay (2 wt%) the modulus can also be significantly improved. Since clay has a much higher modulus than the epoxy matrix, it is easy to understand, based on the rule of mixture, why the modulus of the ENCs can be improved by adding nanoclay. In addition, the modulus of the nanocomposites follows the order  $E_{TS} > E_{HP} > E_{RS} > E_{TM} > E_{Rm} > E_{Epoxy}$ . The level of increase in the modulus of ENCs prepared with the TS, HP, RS, TM, Tm, and Rm methods compared to epoxy is 10.4%, 10.2%, 9.5%, 8.3%, 7.2%, and 5.6% respectively. The results of increase in the modulus event at low clay loading is very well agree with these other reports [ 3, 5, 8].

The dependence of the dispersion of clay in these ENCs on pre-mixing conditions as show in Table 1 follows the order TS > HP > RS > TM > Tm > Rm. Relating to the clay dispersion and the modulus of ENCs, it seems that the better is the dispersion of the nanoclay in ENCs, the higher is their modulus. It can be seen clearly that the modulus of

the ENC prepared with the Tm pre-mixing method is slightly higher than for the Rm method ( $E_{Tm} > E_{Rm}$ ) and the modulus of the ENC prepared with the TS pre-mixing method is slightly higher than for the RS method ( $E_{TS} > E_{RS}$ ). From there, one can see that the stirring temperature has a positive effect not only on the dispersion and intercalation/exfoliation of clay in ENCs but also on the mechanical performance of the ENCs. The pre-mixing speed also shows an effect on the modulus of ENCs. At the same stirring temperature of 120°C, the modulus of ENC prepared with the high-speed pre-mixing method (TM) and without stirring (Tm) ( $E_{TS} > E_{TM} > E_{Tm}$ ). The same is true for stirring at room temperature: the modulus of ENC prepared with the RS pre-mixing method is higher than that of ENC prepared with the RS pre-mixing method is higher than that of the ENC prepared with the RS pre-mixing method is higher than that of the RM pre-mixing method ( $E_{RS} > E_{Rm}$ ). Both stirring temperature and speed show a positive effect on the modulus of ENCs, but the pre-mixing speed appears to have a greater effect.

Unlike the modulus, the strength of the materials depends not only on the dispersion of the clay in the matrix but also on the presence of material defects (voids, holes, etc.), the quality of the interface between clay and matrix, and the structure of the materials. Thus the strength does not necessarily follow the same trends as the modulus. The tensile strength of the ENCs is almost the same as that of the epoxy matrix if standard deviation is considered (Figure 1b). It is well documented in the literature that improvement in tensile strength was reported only for rubbery epoxy systems while for glassy epoxy systems a great reduction in tensile strength was often observed [1, 2, 4, 5, 14, 15]. For example, a substantial loss of 39.5% in tensile strength for glassy ENC was reported by Zilg et al [4]. The reason why nanoclays can improve the strength of only rubbery

systems but not glassy systems is still unclear up to now. In the following study this matter will be better addressed with different explanations. Therefore, the absence of a loss in tensile strength as found in this study should be considered as a positive message, although it would be more gratifying to obtain a gain. If only the average is considered, the general trend of the tensile strength of the ENCs alone in Figure 1b is somewhat similar to the trend of the tensile modulus (except for the sample prepared by HP) in Figure 1a, which means that the strength has a tendency of increasing with the improvement in dispersion. It can be assumed that finer and more uniform dispersion can increase the clay surface area for interacting with the matrix and reduce the possibility of stress concentration in large aggregates that will initiate the failure under stress. Thus the tensile strength is improved. Among them, the sample prepared with TS provides the greatest strength while the poor stirring approach Rm contributes the poorest strength. The exception for HP may be related to the fact that the solvent used in this process was not removed completely from the system.

Tensile properties of epoxy nanocomposites containing different clay concentrations and prepared with high speed at high temperature (TS) or at high temperature without mechanical stirring (Tm) are shown in Figure 2. The modulus increases almost linearly with the clay loading for both mixing methods (Figure 2a). Again, the result shows the advantage of high speed mixing in the formation of nanocomposites, and this advantage becomes greater as the clay loading increases. At the same clay loading, the modulus of the epoxy nanocomposite prepared by high speed is higher than that of the one made without mechanical stirring. For example, at a clay loading level of 6 wt%, the modulus

of the epoxy nanocomposite prepared by the TS method increases by 29.3% with respect to epoxy, compared to 21.3% for the one without mechanical pre-mixing.

The strength of epoxy nanocomposites is also affected by high-speed pre-mixing. The strength of samples with high-speed pre-mixing appears higher than the strength of samples without mechanical pre-mixing, especially at high clay concentrations (Figure 2b). Again it confirms that better dispersion gives better strength. As discussed earlier, the findings in this study are quite superior to much of the data reported in the literature for glassy ENCs, which show only a loss in tensile strength. The increase in tensile strength seems to reach a plateau at 4 wt% clay loading. The tensile strength goes up 12% with 4 wt% of organoclay Cloisite 30B.

Figure 3 shows the compressive properties for epoxy and its nanocomposites prepared by different pre-mixing methods. Once again, the pre-mixing method shows an effect. The presence of clay results in improvement in modulus for all cases of stirring (Figure 3a). In general, the compressive modulus follows the order  $E_{TS} > E_{HP} > E_{RS} > E_{TM} > E_{Tm} > E_{Rm} > E_{Epoxy}$ . The level of increase in the compressive modulus of ENCs prepared with the TS, HP, RS, TM, Tm, and Rm pre-mixing methods compared to epoxy is 10.1%, 8.8%, 5.7%, 3.4%, 2.8%, and 2.4% respectively, which is similar to the increase in tensile modulus. Again, this confirms that the better is the dispersion of the nanoclays in ENCs, the higher is the modulus of the nanocomposites. It also confirms a slightly better advantage of the Tm over the Rm pre-mixing methods, with the TS pre-mixing method being the most advantageous of all. Compressive strength is reduced compared to neat epoxy for the

ENC prepared with the Rm pre-mixing method (Figure 3b) as the result of its poor clay dispersion with large aggregates. Compressive strength increases compared to neat epoxy for ENCs prepared with the Tm, TM, RS, TS and HP pre-mixing methods, and it follows the order TS > HP > RS > TM > Tm > Epoxy. The explanation for this should be similar to that for tensile strength as discussed earlier. The improvement in compressive strength is more significant than for tensile strength because compressive strength is less sensitive to the defects of the testing sample.

Comparing the compressive properties of nanocomposites at different clay loadings for pre-mixing with high speed at high temperature (TS) and without mechanical pre-mixing at high temperature (Tm), the results show a similar trend for both cases, namely an improvement with clay loading, linear in the case of the modulus but more irregular for the strength (Figure 4).

The effects of nanoclay reinforcement on the mechanical properties of the EPON828-D230 system were also investigated by dynamic mechanical analysis (DMA). In the DMA technique an oscillatory force is applied to a sample and the response to that force is analyzed. Two different moduli are determined as a function of temperature, an elastic or storage modulus (E'), which is related to the ability of the material to return or store energy, and an imaginary or loss modulus (E''), which relates to the ability of the polymer to disperse energy. The temperature dependence of the ratio E''/E', also called tan delta (*tan*  $\delta$ ), is related to the mechanical properties of the (nano) composites. The curves in Figure 5 show the dependence of the storage modulus and the loss modulus on temperature, as determined by the three-point bending (flexural) DMA method. The data in Table 3 provide the storage modulus values of the pristine epoxy and the nanocomposite samples at 30°C and 60°C (i.e., in the glassy region below  $T_g$ ) and at 120°C (i.e., in the rubbery region above  $T_g$ ). The percentage of improvement in the storage modulus of nanocomposites compared to pristine epoxy and the  $T_g$  values of the samples (corresponding to the maximum value of *tan*  $\delta$ ) are also provided in Table 3.

The storage modulus in both the glassy and rubbery regions is generally higher for the nanocomposite samples than for the neat epoxy system. However, the level of increase in modulus in the rubbery region is higher than in the glassy region. Clearly, the reinforcing effect of nanoclay is strongly dependent on the nature of the neat polymer and the nanoclay has a more positive effect on mechanical properties in the rubbery region than in the glassy one. With the same 2 wt% of clay in epoxy, the stirring at high speed and high temperature (TS) leads to a better increase in modulus for nanocomposite than the other methods. The better the dispersion of clay in epoxy, the higher is the storage modulus of the nanocomposite (Figure 5a and Table 3). The glass transition temperatures  $(T_g)$  of the epoxy and its nanocomposites are listed in Table 3. It was observed that the presence of nanoclay C30B does not significantly affect the  $T_g$  of the epoxy systems even at different levels of dispersion. C30B, a montmorillonite treated with methyl tallow bis-(2-hydroxyethyl) quaternary ammonium, might be expected to undergo some interaction (for example hydrogen bonding) with the epoxy resin at the temperatures used in the study. Such interaction should increase the  $T_g$  of the system significantly, but this is not the case, probably because the hydroxyethyl groups are "hidden" under the long "tallow" hydrocarbon chains of the intercalant, thus inhibiting a direct interaction between these groups and the epoxy resin.

It can be clearly seen that the storage modulus of the ENC prepared with the Tm premixing method is higher than that of the ENC prepared with the Rm pre-mixing method (but only in the rubbery region), and the storage modulus of the ENC prepared with the TS pre-mixing method is higher than that of the ENC prepared with the RS pre-mixing method. This again confirms the positive effect of pre-mixing temperature on the mechanical performance of ENC.

Stirring speed also shows its effect on the storage modulus of the ENCs. At the same stirring temperature of room temperature, the storage modulus of the ENC prepared with the RS pre-mixing method is higher than that of the ENC prepared with the Rm premixing method. This is similar for stirring at 120°C; the storage modulus of the ENC prepared with the high-speed pre-mixing method (TS) is higher than the storage modulus of the ones prepared with the low-speed pre-mixing method (TM) and without premixing (Tm). Both stirring temperature and speed show a positive effect on the storage modulus of ENC. However, it seems that pre-mixing speed is the dominant factor.

The dependence of the storage modulus and loss modulus on temperature for different clay concentrations in nanocomposites prepared with high speed at high temperature (TS) and at high temperature without mechanical pre-mixing (Tm) is shown in Figure 6. The modulus increases with clay loading. The modulus shows a similar trend for both premixing with and without high speed at high temperature (Figure 6a). However, at the same clay loading, the storage modulus of epoxy nanocomposite prepared by high speed and high temperature (TS) is higher than the one without mechanical pre-mixing at high temperature (Tm).

#### CONCLUSIONS

The presence of Cloisite 30B does not influence the  $T_g$  of the epoxy resin used in this study, but it affects the mechanical properties of the resulting nanocomposites. The presence of clay results in an increase in modulus for all methods of pre-mixing. The better is the dispersion of clay in epoxy, the higher is the storage modulus of the nanocomposite. It is interesting that high speed (RS and TS) can help to break down the aggregates to a sub-micro dispersion and give nanocomposites with strength equal to or even higher than that of the neat epoxy (EPON828-D230). The findings in this study are superior to most other data reported in the literature for glassy ENCs, where only a loss in tensile strength was reported. The increase in tensile strength seems to reach a plateau at 4 wt% clay loading. The modulus is quite linearly proportional to clay loading in the loading range studied. The reinforcing effect of nanoclay is strongly dependent on the nature of the neat polymer, and the nanoclay has a more positive effect on the mechanical properties in the rubbery region (as shown by the DMA results) than in the glassy one.

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#### REFERENCES

- [1] T. Lan and T. J. Pinnavaia, *Chem. Mater.*, **6**, 2216 (1994).
- J. Massam and T. J. Pinnavaia, *Mater. Res. Soc. Symp. Proc. Spring Meeting*, San Francisco, CA, **520**, 223 (1998).
- [3] Nanocor Inc. Web site: <u>www.nanocor.com</u>
- [4] C. Zilg, R. Thomann, J. Finter, and R. Mülhaupt, *Macromol. Mater. Eng.*, 280/281, 41 (2000).
- [5] X. Kornmann, H. Lindberg, and L. A. Berglund, *Polymer*, 42, 1303 (2001).
- [6] A. Yasmin, J. L. Abot, and I. M. Daniel, *Scripta Materialia*, 49, 81 (2003).
- [7] C. Chen and T. B. Tolle, J. Polym. Sci.: Part B: Polym. Phys., 42, 3981 (2004).
- [8] T. Oh, M. Hassan, C. Beatty, H. El-Shall, Journal of Applied Polymer Science, V100, 3465 (2006)
- [9] T.-D. Ngo, M.-T. Ton-That, S.V. Hoa, K.C. Cole, *Polym. Eng. Sci.*, 49:666–672, 2009.
- [10] W. P. Liu, S. V. Hoa, and M. Pugh, Polym. Eng. Sci., 44, 1178 (2004).
- [11] W. P. Liu, S. V. Hoa, and M. Pugh, Compos. Sci. Technol., 65, 307 (2005).
- [12] W. P. Liu, S. V. Hoa, and M. Pugh, Compos. Sci. Technol., 65, 2364 (2005).
- [13] X. Kornmann, H. Lindberg, and L. A Berglund, *Polymer*, 42, 4493 (2001).
- [14] L. A. Utracki, "Clay-Containing Polymeric Nanocomposites", Rapra Technology (2004).
- [15] T. Lan, P. D. Kaviratna, and T. J. Pinnavaia, Chem. Mater., 7, 2144 (1995).

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