

Tensile Properties of Phenol–Formaldehyde Nanoclay Reinforced Composites: A Pilot Study

H. Ku,^{1,2} Y. S. Yap,¹ T. S. Lee,¹ M Trada¹

¹Faculty of Engineering and Surveying, University of Southern Queensland, West Street, Toowoomba 4350, Australia

²Centre of Excellence in Engineered Fibre Composites, University of Southern Queensland, Australia

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ABSTRACT: Phenol–formaldehyde was filled with nanoclay to increase the tensile properties of the composite for structural applications by the Centre of Excellence in Engineered Fiber Composites, University of Southern Queensland, Australia. In this project, we manufactured samples with different percentages by weight of the nanoclay in the composites in steps of 1%; these were then postcured in an oven or microwaves. The samples were then subjected to tensile tests. The results show that the composite with 5 wt % nanoclay produced the highest yield, tensile strength, and Young's modulus, combined with a reasonable fluidity for casting. From 0 to 3 wt % nanoclay, the

yield strengths of the samples postcured in an oven were higher than their counterparts postcured in microwaves. After this, the opposite was true. By extrapolation to 5 wt % nanoclay, it was also found that the tensile strength and Young's modulus of the samples postcured in an oven were lower than their counterparts postcured in microwave irradiation. © 2012 Wiley Periodicals, Inc. *J Appl Polym Sci* 000: 000–000, 2012

Key words: composites; electron microscopy; mechanical properties; resins; strength

INTRODUCTION

Phenolic resins were the first thermoset resins to be synthesized commercially in 1907. These resins are not only low in cost and easy to produce, but they also exhibit excellent fire performance, good dimensional stability, excellent thermal insulation properties, and good chemical and corrosion resistances.^{1,2} These features enable phenolics to be used in myriad applications, such as household appliances, business equipment, wiring devices, and electrical systems.³ Phenolic thermosetting materials were the first major plastic material to be used by industry. They are still among the most widely used thermosets because they are some of the lowest costing engineering materials on a cost-per-volume basis. Phenolics are formed from the condensation polymerization reaction between phenol and formaldehyde. The condensation reaction for phenolics can be carried out under two different conditions, which result in two different intermediate materials. One of the intermediates is called *resole*, and the other is called *novolac*.^{3,4} The various filler amounts used can vary from 50 to 80 wt %. The fillers reduce shrinkage during molding, lower the cost, and improve the strength.

They are also used to improve the electrical and thermal insulating properties and chemical resistance.^{3–8}

Nanocomposites are a type of composite in which the scale of the dispersed phase is less than 100 nm in at least one dimension. Because of the nanoscale dispersion and the high aspect ratios of the inorganic clays, polymer-layered silicate nanocomposites (PLSNs) exhibit light weight, dimensional stability, heat resistance, high stiffness, barrier properties, and improved toughness and strength with far less reinforcement loading than conventional composite counterparts. The synthesis and characterization of PLSNs has become one of the frontiers in materials science.⁸

In general, PLSNs can be divided into two categories: intercalated and exfoliated composites. In an intercalated nanocomposite, a few polymer chains diffuse into the silicate galleries with fixed interlayer spacing. In contrast, an exfoliated nanocomposite is formed when the silicate nanolayers are delaminated and well dispersed in the continuous polymer matrix. The exfoliated state may maximize interfacial contact between the organic and inorganic phases, and as a result, nanocomposites with optimum performance properties can be achieved.⁸

This research project was undertaken to investigate the yield strength, tensile strength, and Young's modulus of phenol–formaldehyde (PF) composites reinforced with various percentages by weight of

Correspondence to: H. S.-L. Ku (ku@usq.edu.au).

nanoclay with a view to finding out the optimum percentage by weight of the nanoclay used in the composites.

PF

The commercial resole resin used in this study was J2027 and was manufactured by Borden Chemical Pty. Its official name is now Hexion Cellobond J2027 L because the company was taken by Hexion.⁹ The catalyst used to crosslink the resin was a phenolic resin hardener catalyst produced by the same company. The official name of the catalyst is Hexion Phencat 15.¹⁰ Hexion Phencat 15 is a mixture of xylene sulfonic acid (70–90%), phosphoric acid (10–20%), and water (1–10%). The ratio by weight of the resin to hardener is 50 : 1, which may differ if the resin is supplied by another manufacturer.

Most molded phenolic parts are made from novolacs. Without fillers or reinforcements, the parts are brittle and have high shrinkage in the mold because of the crosslinked nature of the cured resin. The most common filler is wood flour. Other common fillers and reinforcements are cotton fibers, fiberglass, chopped thermoplastic fibers, and nylon.

The high number of OH groups in the resin gives it excellent adhesive qualities. However, this adhesive nature of phenolics causes molding problems. They tend to stick to the molds. A release agent (Maguiar mirror glaze 8 maximum release agent) has to be applied into the mold surface to solve this problem. The nonflammability of the resin leads to its wide applications. When PF resin is subjected to a flame, it chars rather than melts or burns. It is, therefore, widely applied in situations where avoiding flammability and smoke is vital. Furthermore, the char has a very low thermal conductivity so that surrounding materials are protected by the decomposed phenolic. The low thermal conductivity of the resin promotes its use as bases for toasters and knobs for appliances. Most PF parts are dark because the dark color is inherent to it, and this also limits its use in some applications. A dark pigment is usually added to the resin to standardize the color and to decrease its sensitivity to UV light. Its high electrical resistance wins its applications in electrical switches and circuit breakers. The abrasive nature of the phenolic formaldehyde makes its machining difficult; they are, therefore, molded to near net shape. The resin is cured by condensation polymerization, which results in the evolution of water as a byproduct of the curing process and extensive microvoiding within the matrix. The microvoids have little effect on the composite properties, except that significantly higher water absorption is observed. High water content can cause the structures to delaminate when they are exposed to heat.^{7,8}

NANOCLAY

In addition to a reduction of the cost, the addition of fillers into polymers make them electrically conducting. These fillers must be electrically conducting and are usually discontinuous for the sake of convenience in composite fabrication, for example, in slurry casting. These composites are widely used in electronic packaging.¹¹ Moreover, the addition of some fillers to polymers will increase the heat dissipation capability of the composites. This is very important for the proper operation of electronic devices because the accumulated heat generated from the performance of those devices should be removed quickly.¹²

The filler used in this study was nanoclay. The product name of the nanoclay used was Cloisite 30Bm, which was manufactured by SCP Rockwood Additives; its synonym is organoclay. Cloisite 30B is a natural montmorillonite modified with a quaternary ammonium salt. Cloisite 30B is an additive for plastics to improve various plastic physical properties, such as reinforcement, HDT, CLTE, and the barrier properties. The moisture content is less than 2%. The typical dry particle sizes are 10% less than 2 μm , 50% less than 6 μm , and 10% less than 13 μm . The color is off white. Its density is 1.98 g/cc.¹³

The product may form explosive dust/air mixtures if high concentration of product dust is suspended in air. The material can be slippery when wet. Routes of exposure are through inhalation and eye contact. The toxicity warnings of the nanoclay are as follows. Do not get this material in contact with eyes. Contact may irritate or burn eyes. Eye contact may result in corneal injury. Avoid contact with the skin. Do not breathe dust. Repeated or prolonged inhalation may cause toxic effects such as respiratory irritation. It may cause lung cancer by inhalation in humans. Do not ingest. Prolonged exposure may cause chronic effects. Immediately flush eyes with plenty of water for at least 15 min. Remove contact lenses if present and easy to do. Continue rinsing. Get medical attention immediately. Remove and isolate contaminated clothing and shoes. Wash off with warm water and soap. For minor skin contact, avoid spreading the material on unaffected skin. Get medical attention if symptoms occur. Move to fresh air. If breathing is difficult, give oxygen. Do not use mouth-to-mouth method if victim inhaled the substance. Induce artificial respiration with the aid of a pocket mask equipped with a one-way valve or other proper respiratory medical device. Call a physician if symptoms develop or persist. Rinse mouth if ingested. Do not induce vomiting without advice from a poison control center. If vomiting occurs naturally, have victim lean forward to reduce risk of aspiration. If ingestion of a large

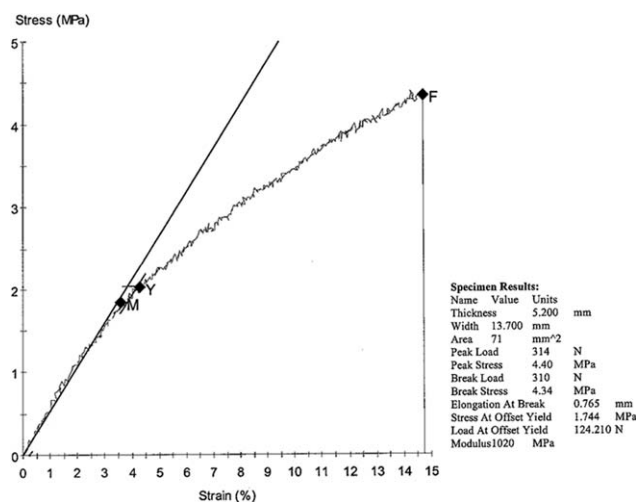


Figure 1 Stress against strain of a sample.

amount does occur, call a poison control center immediately.¹³ The dusts may form an explosive mixture with air. Take precautionary measures against static discharge. Do not use a water jet. Keep the formation of airborne dusts to a minimum. Provide appropriate exhaust ventilation at places where dust is formed. In the case of insufficient ventilation, wear suitable respiratory equipment. Wear personal protective equipment. Avoid prolonged exposure. Wash thoroughly after handling. Handle and open container with care. Guard against dust accumulation of this material. Keep in a well-ventilated place. Keep container tightly closed. Keep out of the reach of children. Use care in handling/storage.¹³

TENSILE PROPERTIES

ISO 527-1 : 1996 (*Plastics—Determination of Tensile Properties*) was the standard used for the tensile tests.¹⁴ A Material Testing Systems 810 instrument was used for the tests. The capacity of the testing machine was 100 kN. The rate of extension (1 mm/min) was in accordance with the standard.

The stress at offset yield (yield strength), tensile strength, and Young's modulus of the composite (1 w/t % nanoclay) can be read from the data given in Figure 1, and these values were 1.744, 4.34, and 1020 MPa, respectively. For each type of composite, there were six samples.

COMPOSITE SAMPLES

The reinforcer was nanoclay (Cloisite 30B), and the composite samples were made at 0–4 wt % filler in the cured PF/nanoclay composites. As the raw materials of the composites were liquid and powder, the tensile test specimens were cast to shape. The resin was a dark brownish liquid and was first

TABLE I
Weight of the Materials Required to Make
1000 g of PF/Nanoclay (30%)

Parameter	Material			
	R	C	R + C	Nanoclay Composite
Percentage by weight	20	1	—	—
Percentage by weight	—	—	96	4
Weight of materials (g) in 300 g of PF/SLG (10%)	914	46	960	40
				1000

R, resin; C, catalyst.

mixed with the dark brownish catalyst. After that, the nanoclay was added to the mixture, and they were then mixed to give the uncured composite. Table I shows the masses in grams of the resin, catalyst, and nanoclay required to make 1000 g of uncured composite of 4 wt % nanoclay. Australian Standard 1145.2 (2001) was followed during the sample preparation.¹⁴

The mixture of the nanoclay, resin, and catalyst was blended with a mechanical blender to ensure a more homogeneous mixture. The upper and lower plates and the mold are illustrated in Figure 2. They were clamped by nine screws and springy plastic clamps as illustrated in Figure 3. This proved to be effective, and no seeping of the slurry took place when the samples were cured under ambient conditions. The screwed and tightened mold combination was slightly vibrated to facilitate the escape of the gases, and this certainly reduced the porosity of the specimens. Finally, before the uncured composite was poured into the mold, the upper surface of the lower plate, the cavities of the mold, the two faces of the mold, and the lower surface of the upper plate were applied with more releasing agent (Maguiar mirror glaze 8 maximum release agent) to enable the easy release of the samples after curing. The uncured composite was then cast into the molds (Fig. 2) to cure in ambient conditions.

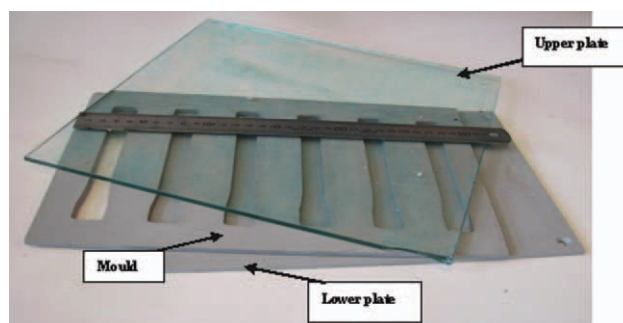


Figure 2 Molds for the specimens. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

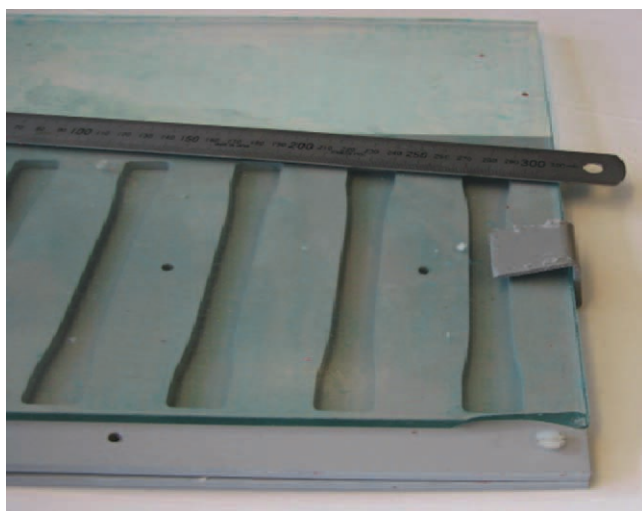


Figure 3 Screwing and clamping of the mold and upper and lower plates. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

After the initial 72-h curing, when the test pieces were removed from the mold, they were postcured. We achieved this by baking the pieces in an oven or microwaves. In oven curing, the oven temperatures and times were as follows:

- 4 h at 50°C.
- 4 h at 80°C.
- 2 h at 100°C.

Microwaves have been investigated as an efficient alternative energy source for polymers and composite processing. Microwave processing offers several advantages over the conventional thermal processing method. These advantages include fast, selective, and volumetric heating, the enhancement of fiber/matrix adhesion, and high controllability. On the other hand, it can cause burn marks on the specimen due to uneven heat distribution during processing.¹⁵ The specimen was heated to 50°C and was then cooled down to room temperature before further processing. The temperature steps were as follows:

- 50°C.
- 80°C.
- 100°C.

The temperature reached at each stage was the same as that of oven postcuring. The power of the microwave facility was 800 W, and the facility could be operated at 10 power levels, ranging from 80 to 800 W in 10 steps. In general, 160- and 240-W power levels were used. The test pieces were then tensile-tested. A Material Testing Systems 810 instrument was used for the tests. The rate of extension was 1 mm/min.

RESULTS AND DISCUSSION

Figure 4 illustrates the yield strengths of PF matrix composites reinforced with various weight percentages of nanoclay. The yield strength of the neat resin postcured in an oven was 1.34 MPa. This rose slowly to 4.07 MPa at 4 wt % nanoclay. It could be argued that the trend would continue with increasing weight percentage of filler. The yield strengths of the neat resin postcured in microwaves was 1.01 MPa. This rose slowly to 4.77 MPa at 4 wt % nanoclay. It was found that from 1 to 3 wt % nanoclay, the yield strengths of the samples postcured in an oven were higher than those of their counterparts. At 4 wt % reinforcement, the yield strengths of the specimens postcured in an oven were lower than their rivals. It could be argued that this trend would continue with increasing weight percentage of nanoclay for some time before peaking at a certain weight percentage of filler. Nanoclay absorbed water readily and became a medium for ion exchange.¹⁶ Composites with a higher weight percentages of nanoclay then had more water molecules, which were polarized with the changing electric field of microwaves. The mechanism involved was interfacial polarization, which resulted in high-frequency heating, and this can happen with a fixed-frequency microwave.¹⁷ This postcured the composites to a higher degree of cure in a short time. The composites were, therefore, stronger than their counterparts postcured in an oven because of the higher degree of cure. Table II shows the values of the yield strengths mentioned previously, with their standard deviations in parentheses.

Figure 5 illustrates the tensile strengths of the phenolic composites with various weight percentages of nanoclay. The tensile strength of the neat resin postcured in an oven was 2.47 MPa. This rose slowly to 7.85 MPa at 4 wt % nanoclay. It could be argued

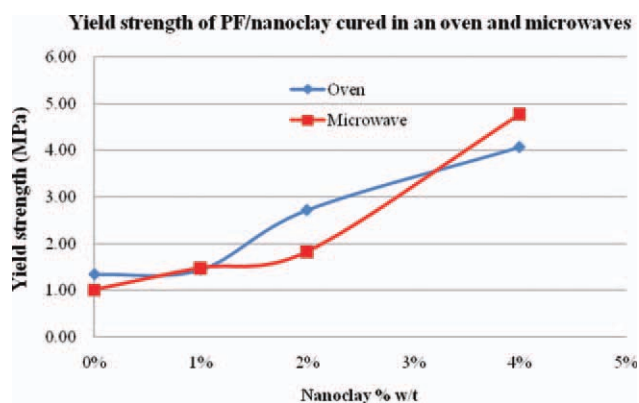


Figure 4 Yield strengths of the phenolic composites reinforced with various nanoclay weight percentages and postcured in an oven and in microwaves. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

TABLE II
Yield Strength, Tensile Strength, and Young's Modulus Values of the Phenolic Composites Reinforced with Nanoclay

Mechanical properties	Nanoclay (wt %)			
	0	1	2	4
Yield strength (MPa) for samples postcured in an oven	1.34 (0.41)	1.44 (0.26)	2.72 (0.69)	4.07 (1.14)
Yield strength (MPa) for samples postcured in microwaves	1.01 (0.26)	1.48 (0.21)	1.82 (0.51)	4.77 (1.13)
Tensile strength (MPa) for samples postcured in an oven	2.47 (0.55)	3.10 (0.56)	4.44 (1.40)	7.85 (1.65)
Tensile strength (MPa) for samples postcured in microwaves	2.06 (0.48)	3.90 (0.39)	3.13 (0.85)	7.73 (2.53)
Young's modulus (GPa) for samples postcured in an oven	1.69 (0.25)	1.67 (0.12)	2.07 (0.26)	2.32 (0.19)
Young's modulus (GPa) for samples postcured in microwaves	1.05 (0.18)	1.18 (0.14)	1.46 (0.13)	2.28 (0.44)

The numbers in parentheses are the standard deviations.

that the trend would continue with increasing weight percentage of filler. The tensile strength of the neat resin postcured in microwaves was 2.06 MPa. This rose slowly to 7.73 MPa at 4 wt % nanoclay. It was found that from 1 to 4 wt % nanoclay, the tensile strengths of the samples postcured in an oven were higher than those of their counterparts. It could be argued that this trend would continue with increasing weight percentage of nanoclay for some time before peaking at a certain weight percentage of filler, and the reason was the same as that for the yield strength. Table II shows the values of the tensile strengths mentioned previously, with their standard deviations in parentheses.

Coal-modified phenolic resin (novolac) and nanoclay particles (5 wt %) were mechanically mixed and subsequently annealed in a vacuum at 140°C for 2 h by Ahmaruzzaman and Sharma.¹⁸ Hexamethylene tetramine (10 wt %) was then added to the mixture. The mixtures were cured at 140°C for 1 h; this was followed by curing at 180°C for 1 h on a compression-molding machine. The neat phenolic resin showed a 1.02-MPa tensile strength.¹⁶ The average tensile strength of the neat resin samples postcured

in an oven found in this study was 2.47 MPa, which was 142% higher than that found by Ahmaruzzaman and Sharma.¹⁸ The average value of the samples postcured in microwaves found in this study was 2.06 MPa, which was still 102% better than that found by Ahmaruzzaman and Sharma.¹⁸ This was due to the fact that Ahmaruzzaman and Sharma¹⁸ used novolac phenolic resin, and resole phenolic resin was used in this study. The tensile strength found by Ahmaruzzaman and Sharma¹⁸ with 5 wt % nanoclay was 4.11 MPa.¹⁶ The average tensile strength of samples (4 wt %) postcured in an oven found in this study was 7.85 MPa which was 91% higher than its rival. By extrapolation, it could be argued that the average tensile strength of samples (5 wt %) postcured in an oven would be 9.56 MPa, which would then be 133% higher than its rival. The average tensile strength of the samples (4 wt %) postcured in microwaves found in this study was 7.73 MPa, which was 88% higher than that found by Ahmaruzzaman and Sharma.¹⁸ By extrapolation, it could be argued that the average tensile strength of the samples (5 wt %) postcured in microwave irradiation would be 10.35 MPa, which would then be 152% higher than that found by Ahmaruzzaman and Sharma.¹⁸ It (10.35 MPa) would also be higher than that of its counterpart (9.56 MPa). With increasing weight percentage of nanoclay, the yields and tensile strengths of the samples postcured in an oven would be lower than their counterparts postcured in microwave irradiation.

The increase in tensile strengths of the composites from those of the neat resin could have been due to two reasons, one from a nanoparticle point of view and the other from crosslinking. If a matrix were more crosslinked, its strength and stiffness would be higher. On the other hand, if nanoparticles were infused into a polymer, they would form a relatively weak particle-polymer interface, which would act as a crack-dissemination mechanism at the very early stage of crack growth and, eventually, delay of the formation of the dominant crack.¹⁸ Thus, the improved tensile strength of the nanocomposites was believed to have been caused by enhanced

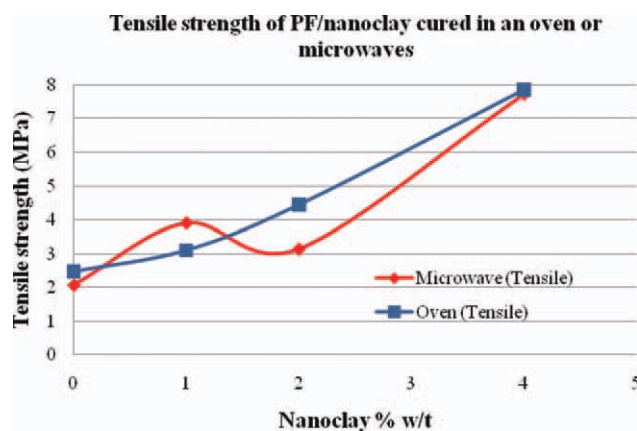


Figure 5 Tensile strengths of the phenolic composite reinforced with various nanoclay weight percentages postcured in an oven and in microwaves. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

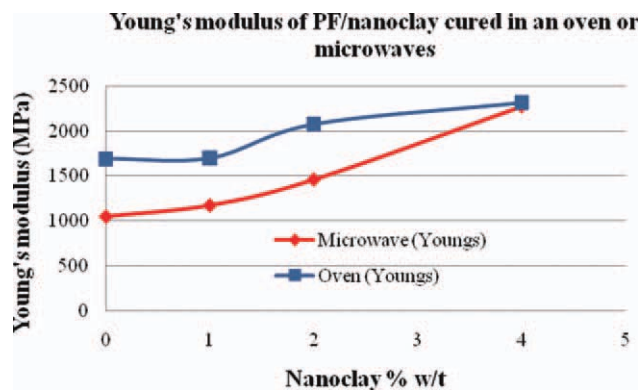


Figure 6 Young's moduli of phenolic composites reinforced with various nanoclay weight percentages postcured in an oven and in microwaves. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

crosslinking in the matrix due to nanoparticle infusion.¹⁸

Figure 6 shows the Young's moduli of various PF matrix composites reinforced with various weight percentages of nanoclay. The Young's modulus of the neat resin postcured in an oven was 1.69 GPa. This rose slowly to 2.32 GPa at 4 wt % nanoclay. It could be argued that the trend would continue with increasing weight percentage of filler. By extrapolation, it could be argued that the average Young's modulus of samples (5 wt %) postcured in an oven would be 2.49 GPa. The Young's modulus of the neat resin postcured in microwaves was 1.05 GPa. This rose slowly to 2.28 GPa at 4 wt % nanoclay. By extrapolation, it could be argued that the average Young's modulus of samples (5 wt %) postcured in microwaves would be 2.85 GPa. It could be found that from 1 to 4 wt % nanoclay, the Young's moduli of samples postcured in an oven were higher than those of their counterparts. However, it could be argued that this trend would not continue with

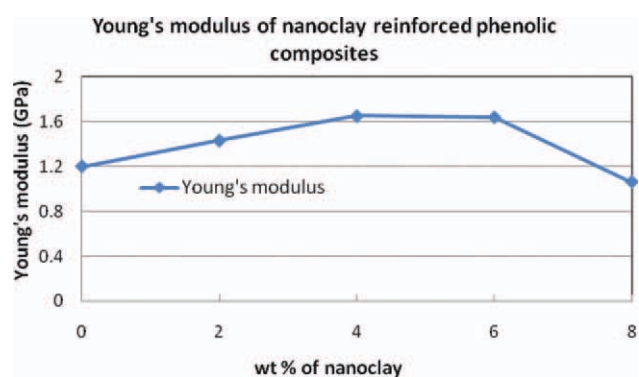


Figure 7 Young's moduli of phenolic composites reinforced with montmorillonite (various weight percentages) and cured thermally at 100–180°C (adapted from ref. 18). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

TABLE III
Results of Plywood Bonded with PF Resins Containing Different Percentages of NaMMT (Adapted from Ref. 15)

NaMMT (wt %)	Tensile strength (MPa)
0	1.43
1	1.42
3	1.40
5	1.44

increasing weight percentage of nanoclay; the reverse would happen because the same phenomenon happened in a study by Pappas et al.,¹⁹ in which phenolic resin and montmorillonite clay were used to make nanocomposites. The results are depicted in Figure 7.¹⁹ The Young's modulus (2.85 MPa) of the samples (5 wt %) postcured in microwaves would be higher than that of its counterpart (2.49 MPa). Table II shows the values of the tensile strengths mentioned previously, with their standard deviation in parentheses.

Pappas et al.¹⁹ developed an *in situ* semibatch polymerization process for making phenolic resin/montmorillonite clay nanocomposites. Montmorillonite clay is in the smectite clay family. It consists of nanometer-thick polysilicate sheets that have a characteristic length between 100 and 1000 nm. The clay has a specific area of 760 m²/g. To take advantage of montmorillonite's high aspect ratio and nanometer-scale thickness, it is necessary that the polymer (or monomer) penetrate the interlayer gallery of the nanoclay (intercalation). The *in situ* method is one of the methods that can accomplish this. In the *in situ* method, the monomer diffuses into the interior clay surface and polymerizes within the platelet galleries.¹⁹ The Young's modulus of the neat resin was 1.20 GPa, which was a little bit lower than that obtained in this study (1.69 GPa) with samples postcured in an oven.

Pappas et al.¹⁹ found that at 2.7% of clay by mass of the montmorillonite is predominantly exfoliated (fully dispersed). At higher clay loadings, a substantial amount of the clay remains in aggregate or intercalated form. When the montmorillonite was exfoliated, the material was mechanically superior. The composite had a tensile modulus that was 21% higher than that of the neat resin.¹⁹ In this study, the Young's modulus of the phenolic composite postcured in an oven with 2 wt % nanoclay was 2.07 GPa, which was 52% higher than that of the neat resin. This was better than the results obtained by Pappas et al.,¹⁹ and it could be argued that the nanoclay in this study was also well dispersed.

Figure 7 illustrates the Young's modulus of phenolic composites reinforced with montmorillonite (various weight percentages), MgO, and glass, respectively, and cured thermally at 100–180°C, as

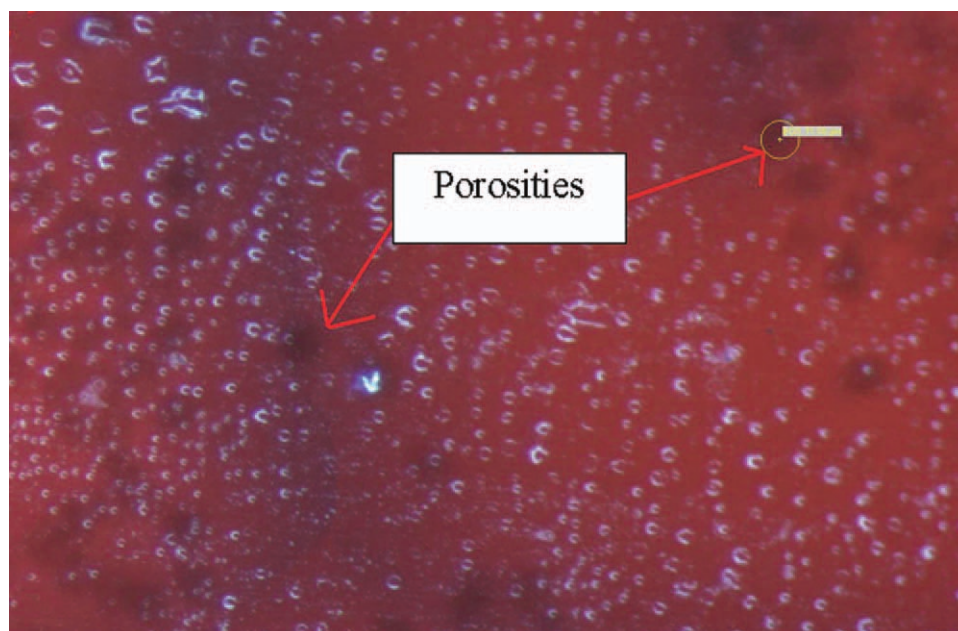


Figure 8 Neat phenolic resin samples postcured in an oven for 4, 4, and 2 h at 50, 80, and 100°C, respectively, at a magnification of 160×. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

obtained by Pappas et al.¹⁹ It could be found that the Young's modulus peaked at 5 wt % montmorillonite; it could, therefore, be argued that the values of the tensile strength and Young's modulus of composites obtained in this study would also peak at 5 wt % nanoclay.

Chan et al.²⁰ used nanoclay to reinforce epoxy resin, and the composites were thermally cured. It

was found that the Young's modulus of the samples with 3, 4, and 5 wt % nanoclay increased by 24, 31, and 34%, respectively, whereas those (postcured in an oven) in this study were 31, 37, and 69%, respectively. It could be found that the improvement from the neat resin for all of the percentages of nanoclay considered were higher than those found by Chan et al.²⁰ However, the resins used were different;

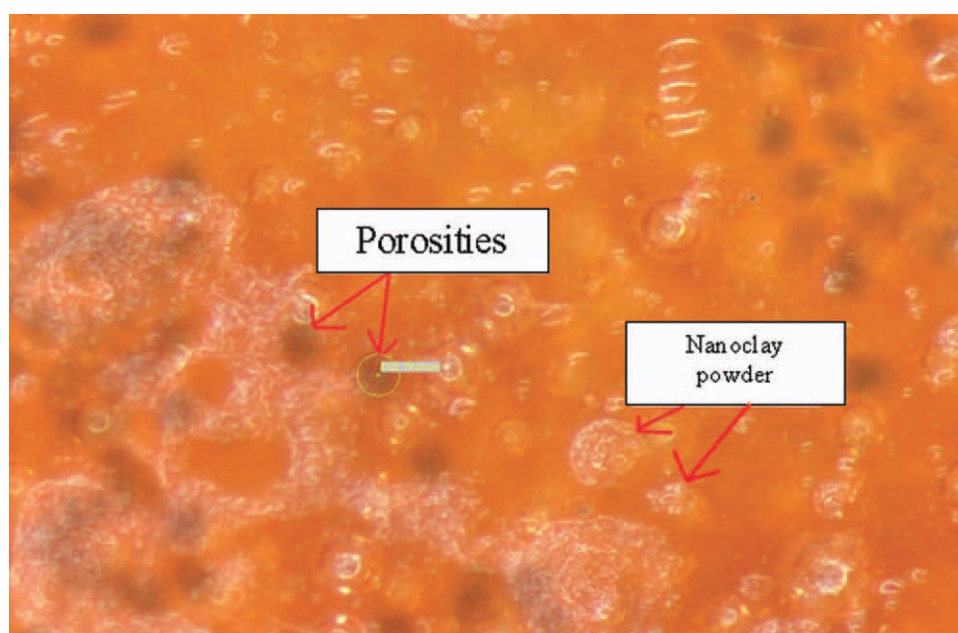


Figure 9 PF/nanoclay (4% w/t) specimens postcured in an oven for 4, 4, and 2 h at 50, 80, and 100°C, respectively, at a magnification of 160×. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

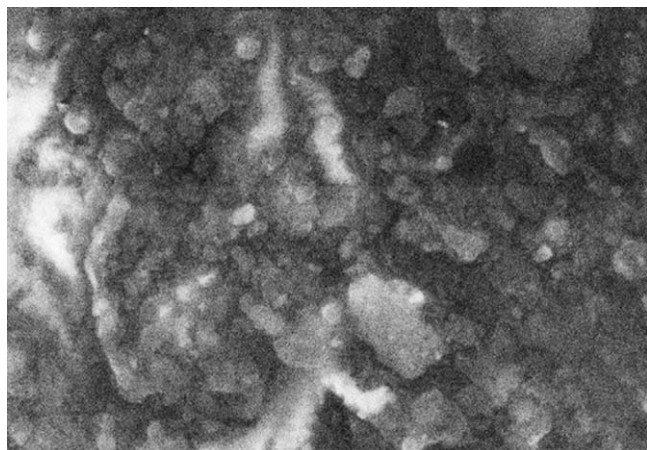


Figure 10 Scanning electron microscopy of the novolac/clay nanocomposite (adapted from ref. 18).

Chan et al.²⁰ used epoxy resin, but resole phenolic resin was used in this study. In Chan et al.'s study,²⁰ it was found that the Young's modulus peaked at 7 wt % nanoclay and was not the predicted 5 wt % in this study;²⁰ this was because Chan et al.²⁰ used epoxy resin, and phenolic resin was used in this study.

Lei et al.²¹ prepared PF resin at a molar ratio of phenol to formaldehyde of 1 : 1.76. The preparation procedure was as follows: 1.5 mol of phenol was mixed with 2.65 mol of formaldehyde (as a 37% formalin solution) in a glass reactor equipped with a mechanical stirrer, a thermometer, and a reflux condenser. Na⁺ montmorillonite (NaMMT) nanoclay was then added at room temperature, and the whole mixture was stirred overnight (12 h). The temperature was then increased to reflux (95°C) in 30 min under continuous mechanical stirring. Once 95°C was reached, 0.25 mol of NaOH (as a 30% aqueous solution) were added in five lots, each lot at a 10-min interval. The mixture was maintained at reflux until the resin reached a viscosity of 400–500 mPa s, measured at 25°C. The resin was then cooled and stored. The resins were tested dynamically by thermomechanical analysis on a Mettler apparatus. The tensile results of plywood bonded with a PF resin containing different percentages of NaMMT are presented in Table III.²¹ It could be found that the tensile strength also peaked at 5 wt % nanoclay, like those predicted in this study. The Young's moduli obtained also peaked at 5 wt % nanoclay.²¹

Figure 8 shows the optical microscopy of the neat phenolic resin samples postcured in an oven for 4, 4, and 2 h at 50, 80, and 100°C, respectively, at a magnification of 160×. It could be found that there were porosities and traces of air bubbles. The PF/nanoclay (4 wt %) specimens postcured in an oven for 4, 4, and 2 h at 50, 80, and 100°C, respectively, at a magnification of 160× are depicted in Figure 9. It could be found that the nanoclay powder was

dispersed quite evenly, but porosities were also found, as in the case of the neat resin. The nanoclay distribution shown in Figure 9 was comparable to that of the novolac/clay nanocomposite (Fig. 10) obtained by Ahmaruzzaman and Sharma¹⁸ in one of their scanning electron microscopy images.

CONCLUSIONS

This study evaluated the yield strength, tensile strength, and Young's modulus of phenolic resins reinforced with various percentages by weight of nanoclay; in all cases, the fluidity of the slurry composite was high, and it could be cast easily into molds. The values of the tensile strength and Young's modulus were also compared with those found by other studies, and the values obtained in this study were generally higher than their rivals. In many cases (this study and others), the values of the tensile strength and Young's modulus peaked at 5 wt % nanoclay. The best weight percentage of nanoclay that could be added to the phenolic resin to give maximum yield strength, tensile strength, and Young's modulus was about 5 wt %. Also, from Table II, it could be found that the standard deviations of the yield and tensile strengths and the Young's modulus were small, and it could be argued that the values of those tensile properties were reliable.

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