

Toughened Epoxy Resin Matrix for a Membrane Shell by Wet Filament Winding

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ABSTRACT: A toughened epoxy resin matrix was obtained with a reactive toughening agent and methyl hexahydrophthalic anhydride as a curing agent. The mechanical properties of the modified epoxy resin and its glass-fiber-reinforced composites were investigated systematically. The modified epoxy resin matrix possessed many good properties, including a high flexural strength (138 MPa), high elongation at break (5.2%), low viscosity, long pot life at room temperature, and good water resistance. In addition, the glass-fiber-reinforced composites

showed a high strength conversion ratio of the glass fiber (86.7%) and good fatigue resistance. The results demonstrated that the modified epoxy resin matrix is very suitable for applications in reverse osmosis membrane shell products fabricated with wet filament winding for water treatment. © 2008 Wiley Periodicals, Inc. *J Appl Polym Sci* 111: 255–263, 2009

Key words: composites; matrix; mechanical properties; toughness

INTRODUCTION

The reverse osmosis (RO) membrane isolation technique is an environmentally friendly and practical water-treatment technology. RO is one of the most effective filtering systems as RO membranes can block all solutes, including inorganic molecules and any organic substances with a molecular weight greater than 100, whereas water molecule can pass through RO membranes freely and be purified. Thus, the RO technique is widely employed to produce highly purified water. The RO membrane shells are designed for continuous, long-term application as housings for RO membranes, which have been extensively used in many water-treatment applications, such as chemicals, foods and beverages, seawater desalination, and pharmaceuticals. Nowadays, because the treatment of polluted water has become increasingly important for environmental protection, the demand for RO membrane shells has increased sharply in China. The fiberglass wound composite membrane shell (a kind of fiber reinforced plastics (FRP) internal-pressure vessel for water treatment, inside which one or more RO membrane are installed; its profile is depicted in Fig. 1) has many

potential advantages over that made of stainless steel, such as a high specific stiffness and strength, good corrosion resistance, and thermal insulation.¹

Filament winding is a continuous-fiber-reinforced composite production technique in which a resin-impregnated band of continuous fibers is wound over a rotating mandrel. The process continues with the winding of additional layers until the design requirements are achieved. The production is accomplished by the curing of the filament-wound product in an oven and the removal of the mandrel. Filament winding has matured to become the major manufacturing process in the mass production of advanced fiber-reinforced composites such as pipes and internal pressure vessels, that is, wound outer shells for solid rocket motors, pipes and shafts, and cylindrical structures. There are two major winding methods: (1) in wet winding, the fibers are passed through a resin bath as they are wound onto a rotating mandrel, and (2) in prepreg winding, the prepreg-impregnated fiber tows are placed on a rotating mandrel.² For fiber-reinforced thermosetting matrix cylinders, wet winding is more commonly used because of its lower material cost and shorter winding times in comparison with prepreg winding; moreover, the resin formulation can be varied to meet specific requirements for different parts.³ Thus, wet filament winding is very suitable for manufacturing membrane shell products.

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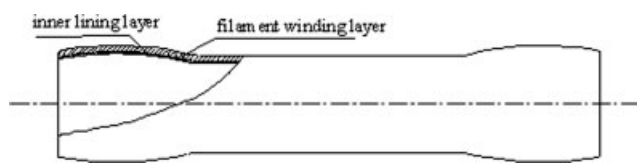


Figure 1 Profile of the filament-wound RO membrane shell for water treatment.

The resin matrix for a filament-wound membrane shell should possess high mechanical properties, good interfacial adhesion with the fiber, and excellent water resistance because a membrane shell often is used under high pressure over the long term. Among the common thermosetting resins, epoxy resin is often selected as the resin matrix of membrane shells because of its good overall mechanical properties, very low water uptake and coefficient of thermal expansion, easy processing, and excellent chemical resistance. However, epoxy resin must be toughened when used as the matrix of wound composites because of its brittleness; otherwise, the matrix may crack and cause the membrane shell to leak at a high pressure, and this could result in the failure of the product.^{4,5}

In this study, we attempted to develop a toughened epoxy resin system suitable for wet-filament-wound membrane shells. For this purpose, a trifunctional group epoxy resin was chosen as the reactive toughening agent in the formulation. Moreover, the viscosity, pot lifetime, and mechanical properties of the epoxy system were examined, and the water resistance and mechanical properties of the fiber-wound membrane shells were investigated.

EXPERIMENTAL

Materials

The epoxy resin used in this work was the bifunctional epoxy resin diglycidyl ether of bisphenol A (DER-331; Dow Corp., Greater China Corp., Zhangjiang, China), which had an epoxy value of 0.52–0.53. The toughening agent (trade name 6360) was supplied by Shanghai Xinhua Resin Factory (Shanghai, China). The curing agent was methyl hexahydrophthalic anhydride (MeHHPA) from Shanghai Shengyuan Co. (Shanghai, China), and the cure accelerator was 2,4,6-tri(dimethylaminomethyl) phenol (DMP-30) from Shanghai Haitai Co. (Shanghai, China). Continuous E-glass fiber roving (1200 tex, 17- μm diameter; type ERS120-T980) was used as a reinforcement and was purchased from Taishan Fiber Co. (Taian, China).

The chemical structures of the epoxy, toughening agent, curing agent, and accelerator are shown in

Table I, and the properties of the epoxy resin and glass fiber are listed in Table II.

Sample preparation

Preparation of the cured epoxy resin by casting

The epoxy resin was added to the curing agent, toughening agent, and accelerator according to the designed mass fraction ratio (as shown in Table III) and mixed homogeneously. Then, the mixture was degassed for about 30 min to get rid of bubbles. After that, the blend was transferred into an open stainless steel mold kept at 60°C and was cured in an oven with the following curing procedure: 90°C for 1 h, 110°C for 2 h, and 140°C for 2 h. After curing, the blend was allowed to cool slowly to room temperature.

Filament-wound, ring-shaped sample fabrication

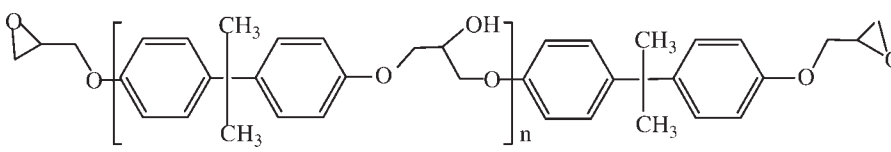
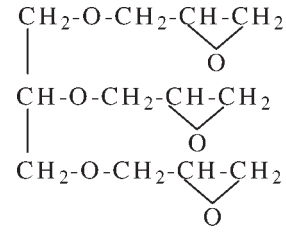
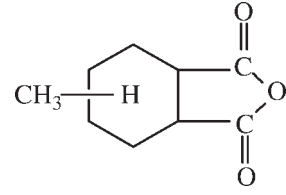
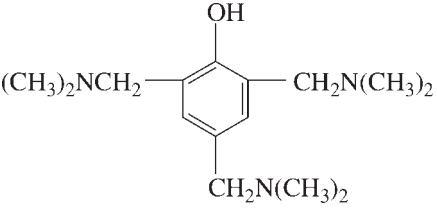
The unidirectional-filament-wound, ring-shaped sample, that is, a Naval Ordnance Laboratory (NOL) ring (shown in Fig. 2), was produced with a filament winding machine (type WSV-2, 43rd Research Institute of Aerospace, Xi'an, China) according to GB2578-81. The continuous glass fibers were wetted by passage through an epoxy resin bath for impregnation just before they were wound onto the steel mandrel, for which only hoop winding was used. During the whole filament winding process, the fiber tension was kept at 10 N. Then, the filament-wound samples were put into an oven and cured with the same curing procedure used for the pure epoxy system. After that, they were cooled slowly to room temperature, and the NOL samples were removed from the steel mandrels. Finally, the test samples were cut down to 150 mm in diameter, 2 mm in thickness, and 6 mm in width.

Filament-wound membrane shell product fabrication

The membrane shell product consisted of an inner lining layer serving to water-proof the product and an outer filament-wound layer imparting mechanical strength to the product.

Inner-lining-layer preparation. The inner-lining-layer preparation involved the following procedures: (1) carefully pouring the liquid epoxy adhesive prepared according to Table III onto the surface of the slowly rotating steel mandrel, from one end to the other, to ensure that the whole surface of the mandrel was completely coated with a thin layer of epoxy adhesive; (2) helically winding the coated steel mandrel at an angle of 75° with a glass bat with a density of 40–45 g/cm³; and (3) repeating the previous operation but replacing the glass bat with a

TABLE I
Chemical Structures of the Materials

Material	Chemical structure
Epoxy resin (DER-331)	
Toughening agent (6360)	
Curing agent (MeHHPA)	
Accelerator (DMP-30)	

fibrous glass mat with a tension of 50 N. Great care had to be taken to ensure that the entire glass bat and fibrous glass mat were wetted completely [see Fig 3(a)].

Outer-wound-layer fabrication. The resin viscosity was kept as low as possible to wet the fiber best. During the whole filament winding process, the fiber tension was kept at 100 N, and the rotating speed of the mandrel was 65 rpm. Helical winding was used first for the angle of 55°. After helical winding was finished, hoop filament winding was used at the angle of 90°

[see Fig. 3(b)]. The resin content of the wound layer was controlled to be about 35%, and the thickness of the wound layers was dictated by the applied internal pressure. The filament-wound products were cured according to the designed cure schedule and were rotated slowly during the entire cure to prevent epoxy adhesive dripping and sagging. The cure process, including heating and cooling, was approximately 5 h in duration. The cured composite membrane shell was then extracted from the steel mandrel by the mandrel being pulled through a brass eye.

TABLE II
Properties of the Neat Epoxy Resin and Reinforcement

	Tensile strength (MPa)	Tensile modulus (GPa)	Elongation at break (%)	Density (g/cm ³)
Neat epoxy	65	3.5	1.1	1.2
E-glass fiber	1600	72	2–3	2.6

TABLE III
Epoxy Resin Formulations for the Wet-Filament-Wound Membrane Shells

Formula	Epoxy DER-331 (g)	MeHHPA (g)	6360 (g)	DMP-30 (g)
1	80	90	20	0.8
2	100	85	0	0.8



Figure 2 Ring-shaped, unidirectional-filament-wound sample. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Characterization

The mechanical strength tests of the cured epoxy resin were performed on a screw-driven universal testing machine (type ZMGI 250, Shenzhen New SANS Co., Shenzhen, China) at a crosshead speed of 2 mm/min to determine the tensile, flexural, and compressive strengths with GB/T1040-1992, GB9341-2000, and GB/T1042-1992, respectively. The impact strength of the cured epoxy resin was measured on a pendulum impact tester (type ZBC1251, Shenzhen SANS Co.) according to GB/T1043-1993.

The interlaminar shear strength and flexural strength of the NOL ring samples were determined on a short-beam-shear fixture and a short-beam-bending test fixture (type ZMGI 250, China) according to GB1461-78 and GB1460-78. The tensile strength of the NOL ring samples was determined on a split-disk fixture (1196 universal testing machine, Instron (Shanghai) Test Equipment Co., Shanghai, China) with GB1451-71.

The viscosity of the epoxy system was measured on a rotational viscosimeter according to GB7193-1987. The fatigue resistance and hydrostatic explosion tests of the filament-wound membrane shell products were measured on hydraulic test devices supplied by the 43rd Research Institute of Aerospace. The morphology of the fracture surface of the cured epoxy resin parts was determined with scanning electron microscopy (AMARY-1000B, KYKY Technology Development Co., Beijing, China).

RESULTS AND DISCUSSION

Epoxy formulation designation

An epoxy system suitable for a membrane shell with wet filament winding must be in accordance with

the following requirements: (1) a low viscosity, (2) a long pot lifetime, and (3) a cured epoxy resin possessing good mechanical properties.⁶

Diglycidyl ether of bisphenol A has been widely used in many industrial fields because of its good mechanical and electrical properties, relatively low cost, and other good properties. Thus, in this study, we selected the DER-331 epoxy (epoxy value = 0.52) as the matrix for the filament-wound membrane shell.

At room temperature, liquid curing agents are the best choice for wet filament winding technology because of their low viscosity. The curing agent in this study had to meet all the following requirements: (1) a liquid state at room temperature and low viscosity, (2) low cost and low toxicity, and (3) a long pot life (at least 3 h under 25°C). Among the many liquid amine curing agents, it was difficult to select one for the epoxy system suitable for this study because many curing agents meet only some of the requirements mentioned previously. However, liquid acid anhydride agents are suitable for wet filament winding of a membrane shell because they can hardly react with epoxy resin and have a low cost, a very long pot life at 25°C, and low toxicity; thus, they completely meet the requirements. Among the liquid acid anhydrides, MeHHPA was chosen as the curing agent for this study because of its good mechanical properties and the light color of its cured parts (MeHHPA imparts to cured epoxy ultraviolet light resistance and does not lead to product yellowing because of an absence of C=C

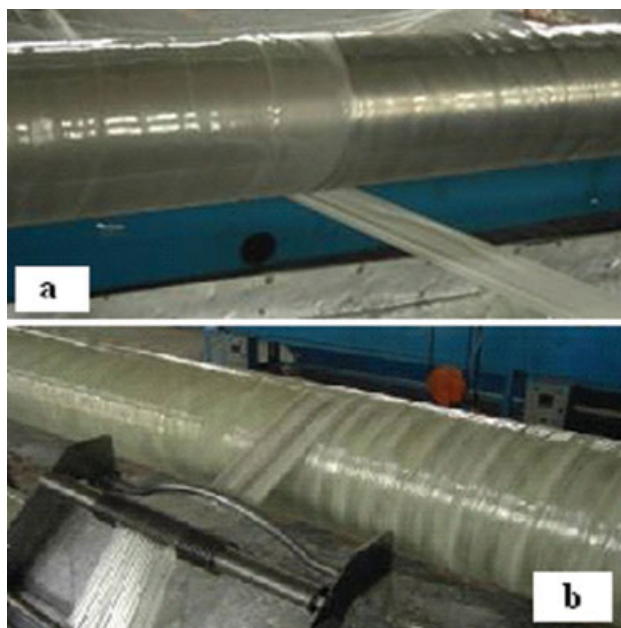


Figure 3 Schematic fabrication process of the filament-wound membrane shell product: (a) inner-lining-layer preparation and (b) outer-wound-layer manufacturing. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

double bonds in its chemical structure).⁷ Because the curing temperature of MeHHPA is a bit high, adding a cure accelerator to MeHHPA can lower the curing temperature to the desired level. Therefore, we selected DMP-30 as an accelerant for the epoxy system.

Filament-wound membrane shells often must endure various inner pressures ranging from 2.5 to 12.5 MPa according to the different types encountered during long-term use. Therefore, to improve the impact strength resistance of the products, a toughened epoxy matrix was needed in this study. The toughening agent had to be used to overcome the brittleness of the cured epoxy because the impact property of the filament-wound layer would depend on the impact property of the epoxy matrix to a great extent. In this study, we used an epoxy resin with trifunctional epoxy groups (6360) as the reactive toughening agent. 6360 could react with the curing agent and become a part of the crosslinking network; in this way, a few flexible chains were introduced into the network structure. Thus, the cured epoxy networks obtained better molecule movement capability than the epoxy system without 6360. The use of 6360 slightly decreased the glass-transition temperature and modulus of the cured epoxy. However, the practical maximum use temperature of the membrane shell product was 50°C; therefore, adding an adequate amount of 6360 to the epoxy not only improved the strength and toughness of the cured epoxy but also had no adverse influence on the practical use of the products.

To satisfy the requirements of the viscosity of the resin matrix and its wettability to the glass fiber in the filament winding process, a viscosity diluter is often added to the epoxy system. However, both the tensile strength and modulus are reduced, whereas the elongation is improved, with the addition of the diluter. In this study, we no longer used a viscosity diluter agent because the toughening agent 6360 also served as the reactive dilute agent for the epoxy resin. Thus, the use of 6360 improved the tensile strength and elongation at break of the epoxy matrix and reduced the viscosity of the epoxy system because of its own low viscosity at the same time. In addition, 6360 possesses many advantages over commonly used inorganic inert solvents such as acetone, which leads to voids upon evaporation. Therefore, the use of 6360 in an epoxy formulation not only reduces the viscosity but also enhances the tensile strength and elongation at break in comparison with other diluters.⁸

The formula for the epoxy system for the membrane shell is listed in Table III.

Mechanical properties of the cast epoxy resin

The mechanical properties of the number 1 and 2 cured epoxy resins are summarized in Table IV.

TABLE IV
Mechanical Properties of the Cast Epoxy

	Formula	
	1	2
Tensile strength (MPa)	77.1 ± 3	65.3 ± 4
Tensile modulus (GPa)	3.3 ± 0.15	3.6 ± 0.13
Elongation at break (%)	5.2 ± 0.14	1.6 ± 0.12
Impact strength (kJ/m ²)	34 ± 2.3	12 ± 2.1
Flexural strength (MPa)	138 ± 6	115 ± 8
Flexural modulus (GPa)	3.4 ± 0.14	3.5 ± 0.11
Compressive strength (MPa)	97 ± 4.1	112 ± 3.8

When 20 wt % 6360 (the toughening agent) was added to replace the same amount of the epoxy (DER-331) in the formulation, the elongation at break and impact strength improved 225 and 196%, respectively. Additionally, the tensile strength and flexural strength increased, whereas the tensile modulus and compression strength decreased. A possible reason could be attributed to the fact that the incorporation of 6360 into the epoxy system introduced a few flexible chains containing ether bonds inside the network structure of the cast. As a kind of trifunctional group epoxy resin, during the curing reaction, toughening agent 6360 and epoxy resin DER-331 reacted with the curing agent nearly at the same time. Thus, many flexible chain segments were crosslinked to the cured epoxy network structure and finally embedded into the structure of the cured epoxy. Consequently, compared to the epoxy system without 6360, the cured epoxy showed a small increase in the crosslinking density leading to improved tensile strength and flexural strength and better movement ability of the chain segments adjacent to crosslink points, which caused higher impact strength.⁹ The improvement in the impact strength could be due to the following two reasons: on the one hand, a few flexible chains containing ether bonds (compared to DER-331) were introduced into the cured epoxy resin, providing the cured epoxy with higher impact strength; on the other hand, the crosslinking density of the cured epoxy did not increase obviously because of only 20 wt % 6360. Therefore, the chain segments of the cured epoxy got much more movement capacity.

Figure 4 reveals the failed fracture surfaces of the anhydride-cured epoxy resin and its blend with 6360. The fracture surface of the neat epoxy resin showed typical characteristics of brittle fracture. The surface was smooth, and the crack propagated uninterruptedly. Meanwhile, the fracture surface of the blend epoxy was rough and showed a ridge pattern, and the river marks could be seen on the fracture surface. This was an indication of crack path deflection; that is, the crack deviated from its original plane, and the area of the crack increased. Here, the

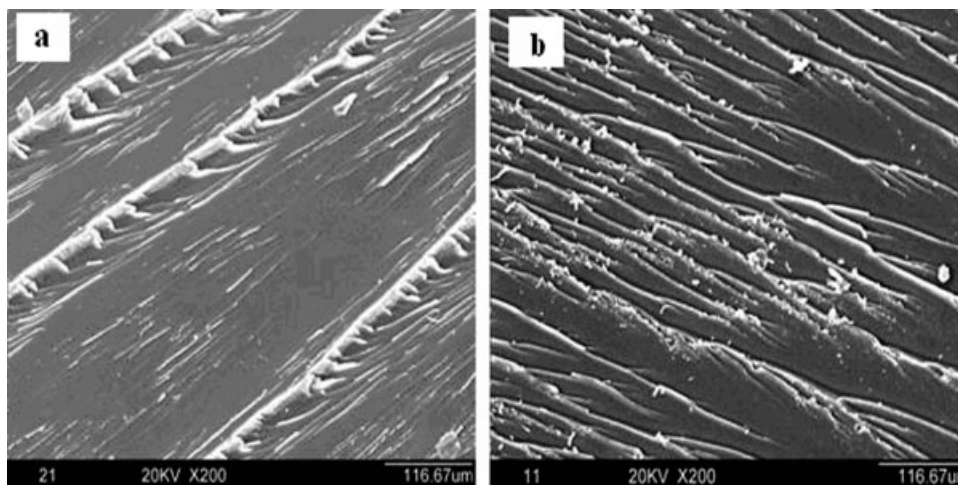


Figure 4 Scanning electron micrographs of the fracture surfaces of (a) the neat epoxy resin and (b) the toughened epoxy (20% 6360/diglycidyl ether of bisphenol A).

energy required for the propagation of the crack increased, so the roughness of the number 1 epoxy system was improved.

On the basis of these results, the number 1 formulation was chosen as the candidate because of its good overall mechanical properties.

Viscosity and pot life of the epoxy system

An epoxy matrix with low viscosity and good wettability to glass fibers is more necessarily recommended for the dynamic wet filament winding process. With respect to the wet filament winding of membrane shells, the viscosity and pot life of the epoxy resin system are crucial because a low viscosity and a long pot life make the winding process easier. Therefore, the viscosity of the epoxy resin system has to be kept as low as possible to wet the fiber completely. If the pot life is too short, it is difficult to finish the wet winding operation because the passing fiber bands cannot be wetted fully by the epoxy resin; the short pot life causes many air bubbles to be trapped inside the resin during the wet winding process if the viscosity increases quickly.¹⁰

The viscosity of the number 1 and 2 epoxy systems as a function of time at 20°C is illustrated in Figure 5. The viscosity of the number 1 epoxy system increased very slowly within 4.0 h, from 0.40 Pa s at the initial time to 0.95 Pa s at 4.0 h. The number 2 epoxy system had a higher viscosity than the number 1 system because of the low viscosity of 6360 versus that of DER-331. Thus, the number 1 epoxy system facilitated wet fiber winding processing because of its low viscosity. Because at room temperature MeHHPA could hardly react with the epoxy and 6360 on account of the high reactive activation energy, only a very small amount of DMP-30 reacted with epoxy slowly. Therefore, the

number 1 epoxy system had a long pot time and a low viscosity facilitating the wet winding operation going well.

Mechanical properties of the epoxy/glass-fiber NOL ring specimens

The NOL ring (shown in Fig. 2) is one kind of a filament-wound epoxy composite; it not only can reflect the ability of the composite to transfer load but also can assess the interfacial adhesion of the composite. For example, some properties, such as the surface wetting of the fiber and the interfacial adhesion strength between the fiber and matrix, can be obtained by the measurement of the ILLS, flexural strength, and tensile strength of an NOL ring sample. Furthermore, the tested results of NOL ring samples provide some basic processing technology

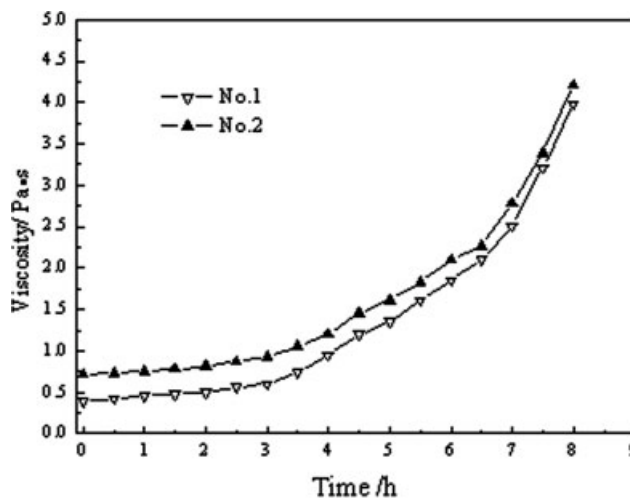


Figure 5 Variations of the viscosity of the epoxy resin systems with time at 20°C.

TABLE V
Mechanical Properties of the Modified-Epoxy/Glass-Fiber Ring Composites

	Formula	
	1	2
Tensile strength (MPa)	1443 ± 85	1178 ± 91
Tensile modulus (GPa)	57 ± 3.1	66 ± 3.5
Shear strength (MPa)	47 ± 2.1	35 ± 2.4
Flexural strength (MPa)	1648 ± 120	1433 ± 115
Strength conversion ratio of the glass fiber (%)	89.6 ± 4.2	73.6 ± 4.6

parameters for a fiber-wound internal-pressure vessel.¹¹

As is well known, the interface/interphase plays a vital role in stress transfer from one fiber to another in the matrix of a composite. Optimal interfacial adhesion is required for taking advantage of the excellent mechanical properties of glass fibers in composites. The property of the matrix resin has an effect on the mechanical properties of reinforced composites through the interface because the toughness, strength, and viscosity of the resin matrix affect the bonding strength and interfacial behavior between the matrix and fiber; furthermore, they affect the mechanical strength of the composites. Therefore, the matrix resin directly has an influence on the strength conversion rate of the glass-fiber reinforcement through the interfacial boundary. To investigate the effect of matrices with different physical properties on the exertion strength of fibers, the concept of the strength conversion rate of the glass fiber for fiber-reinforced composites is introduced.

Here we calculate the strength conversion rate of the glass fiber for fiber-wound composites with the following equation:⁶

$$C = F_a/F_b \quad (1)$$

where C is the strength conversion rate of the cyclic fiber (%) and F_a and F_b are the allowable tensile strength of the cyclic fiber (N) and the tensile strength of the fiber multifilament (N), respectively.

Therefore, the effect of the matrix resin on the exertion strength of the fiber could be examined by the computation of the strength conversion rate of the cyclic fiber.

The strength conversion rate of the cyclic fiber is dictated by the toughness of the matrix, bonding strength, and wetting-out between the fiber and resin. The high strength conversion rate of the cyclic fiber means good interfacial wetting and adhesion strength between the matrix and fiber and full exertion of the high specific strength and modulus of the glass fiber.

The filament-wound NOL ring samples were obtained with formulations 1 and 2 as the matrices and the E-glass fiber as the reinforcement. The test results are summarized in Table V, and they indicate that the tensile strength, shear strength, and flexural strength of the 6360-toughened epoxy/fiber composites reached 1443, 47, and 1648 MPa versus 1320, 35, and 1433 MPa for the neat-epoxy-resin-based composites, respectively; furthermore, the strength conversion ratio of the glass fiber for the number 1 epoxy system improved by 16%. The improved mechanical properties and strength conversion ratio of the glass fiber for the number 1 epoxy system NOL ring composites can be mainly ascribed to the higher toughness and lower viscosity versus the number 2 epoxy system. Therefore, the experimental results demonstrate that for the number 1 NOL ring samples, there had to exist better interfacial wetting and adhesion strength at the interfaces versus the number 2 NOL ring samples. The good interfacial wetting and adhesion strength facilitated the stress transfer from one fiber to another in the matrix of the composite, and the high specific strength and modulus of the continuous fiber were fully exerted.¹²

Mechanical properties of the filament-wound membrane shell

Three membrane shell product samples named A, B, and C (300 psi, 8 in.) were produced at the filament winding facilities with the number 1 epoxy system as the matrix with wet winding. After they were

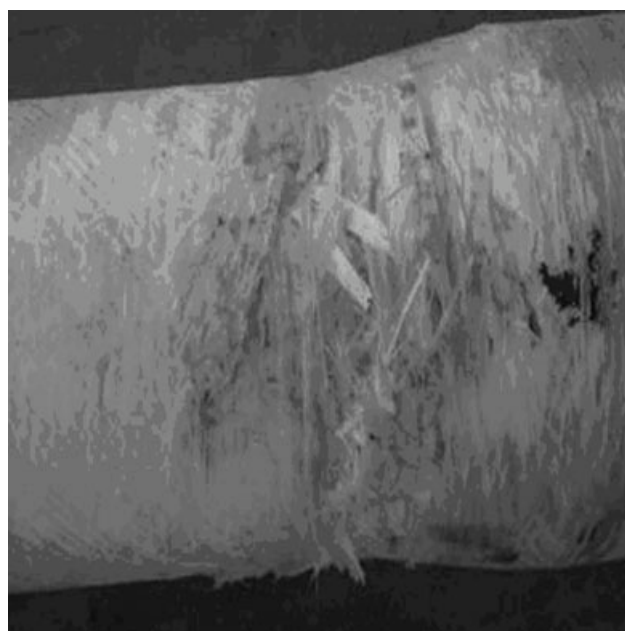


Figure 6 Photograph of the blasted membrane shell product with a blast strength of 12.7 MPa.

TABLE VI
Blast Results of the Membrane Shell Product

	Formula			Average
	A	B	C	
Designed blast strength (MPa)	125	125	125	125
Practical blast strength (MPa)	126 ± 6	130 ± 7	127 ± 5	128
Strength conversion ratio of the glass fiber (%)	85.2 ± 3.2	88.7 ± 3.8	86.5 ± 3.4	86.7
Blast place	Near the end			

cured, the fatigue-resistant property test was conducted according to the practical work conditions of membrane shell products. A fabricated membrane shell often bears various internal pressures; the maximum operation pressure is near 2.5 MPa. One cycle of varying internal hydrostatic pressure is 0 MPa → 2.5 MPa → 0 MPa; here, the same cycles were applied to the product numerous times to test its fatigue-resistant property over the long term at a rate of 25 cycles per minute. The results show that the membrane shells were capable of bearing 100,000 fatigue cycles with no leakage and damage detected at the applied operating pressure. The excellent fatigue resistance could be partially attributed to the good toughness of the number 1 epoxy system because the toughened matrix could restrain and terminate the crack propagation or deflect the original path of the crack and, furthermore, absorb much energy required for crack propagation.

According to the membrane shell product usage requirements, each membrane shell product has a maximum bearing pressure ensuring the safe use of the product, that is, the blast strength, which is about 5 times the normal operation pressure. To verify if the practical blast strength is close to or equal to the designed blast strength or not, the internal hydrostatic explosion tests were performed on the three prepared product samples, that is, A, B, and C. Three damage mechanism stages—whitening, leakage, and final failure—were recorded during the failure tests; moreover, the blast results are depicted in Figure 6 and Table VI. As the results show, the membrane shells made from the toughened number 1 epoxy system exhibited slightly higher burst strength than the designed blast strength value, together with a high average strength conversion rate of the cyclic fiber of 86.7%. This can be ascribed to the higher toughness of the epoxy matrix, the good interfacial wetting and adhesion strength between the matrix and fiber, and the low viscosity of the epoxy system, which reduced the wear between fibers.

Water resistance

Because RO membranes are employed for water treatment, the inner walls of the membrane shells

(the housings for RO membranes) are in close contact with water. Naturally, the cured epoxy system must stand up well to water for very long times; otherwise, water will penetrate the thin epoxy layer, degrade the inner lining layer of the membrane shell, and reduce the mechanical strength of the outer wound layer. Finally, the membrane shell could leak water under the operation pressure. The tested specimens were made from cast number 1 epoxy and number 2 epoxy, and these specimens were immersed in tap water for 360 days at 30°C. The water immersion test was conducted according to the practical working conditions. The results are plotted in Figure 7. The cast number 1 epoxy and number 2 epoxy possessed good water resistance; the number 1 epoxy exhibited better water resistance than the number 2 epoxy because of the slightly higher crosslink density. For the number 1 epoxy, the amount of water increased gradually up to 0.4% before 120 days; after 120 days, the amount of water increased very slowly, and it stopped increasing after 240 days. Furthermore, the whole amount of water was less than 0.5% within 360 days. The results demonstrate that the cast epoxy stood up to water well and met the requirements of inner lining layers because of the excellent water

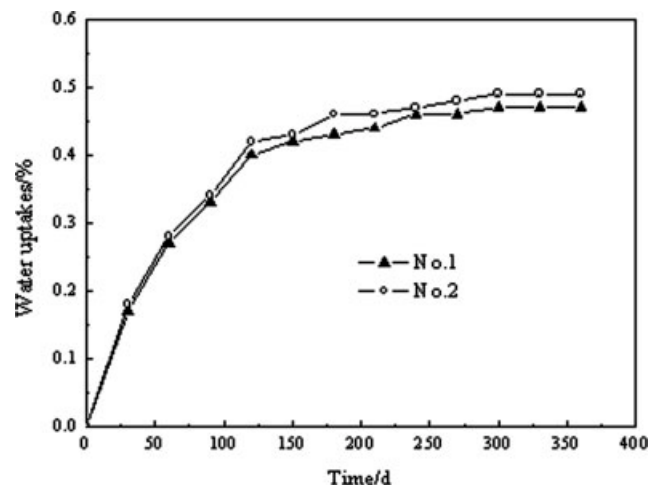


Figure 7 Water uptake of the cast epoxy as a function of the immersion time.

resistance of the molecule structures of the epoxy and MeHHPA.^{13,14}

CONCLUSIONS

This study concerns the development of a toughened epoxy system suitable as a matrix for wet-filament-wound membrane shells. To achieve that goal, the highly effective toughening agent 6360 and liquid anhydride MeHHPA were used in the formulation. Examinations of the viscosity and mechanical properties indicated that the epoxy system had a long gel time (≥ 4 h) and low viscosity (≤ 1.0 Pa s) at room temperature. Furthermore, the results for the mechanical properties demonstrated that the developed membrane shell had good overall mechanical and fatigue properties, a high blast strength, and a high strength conversion rate of the cycle fiber that reached as high as 86.7%. The fatigue resistance and burst experimental results proved that the toughened epoxy system had quite outstanding performance and could be suitable for use in RO membrane shells for water treatment.

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