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Moisture absorption and mechanical degradation studies of PMI foam cored fiber/epoxy resin sandwich composites

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Abstract
The present paper explores the result of hygrothermic aging of polymethacrylimide (PMI) foam core sandwich composites immersed in different temperature deionized (DI) and sea waters. The prepared specimens were tested for moisture up-take behavior and the resulting property degradation in terms of flexural and flat wise compressive strength. The results indicate that the saturated hygroscopic time of specimens immersed in low temperature water and high temperature water is about 480h and 720h, respectively. Due to the presence of ionic in sea water, the specimens immersed in sea water have higher compressive and flexural strength than specimens immersed in DI water.

Keywords: Sandwich structure, PMI foam, Moisture absorption, Mechanical degradation

I. Introduction

Polymer foam cored sandwich composites are widely used in load-bearing components in buildings and naval structures because they can provide high strength and stiffness without significantly adding weight and the cost [1~3]. To improve reliability in using sandwich composites, it is essential to understand their mechanical responses in terms of stresses and deformations under external mechanical and environmental stimuli [4~7]. Extreme temperature changes and humid environmental conditions can significantly degrade the stiffness and strength of the polymer foam core, which intern degrades the performance of the entire sandwich structure [8~10]. High resistance of sandwich composites to these environments is a primary requirement especially when these materials are to be used under marine ambiance.

Several theoretical as well as experimental studies have been reported in literature with respect to the characterization of foam and their sandwich structures [11~15]. Anqi Dong and Yuexin Duan [16] have carried out the hygrothermal condition on the properties of PMI foams cored sandwich structure. They observed a drop of 35% of compressive strength for water saturated sandwich composites. The effect of water immersion on the compressive properties of syntactic foams has been reported by Nikhil Gupta and Eyassu [17]. These composites when immersed in DI water and sea water at 25 and 70°C for over 700h, experienced significant moisture absorption and hence reduction in the flexural modulus and strength of the composites. The effect of sea water on the fracture toughness of sandwich system consisting of wood/plywood/PU/Core mat as core materials and E-glass/polyester face sheet has been reported by Kolat et al [18]. They observed that the fracture toughness of sandwich system with wood and plywood cores decreased, whereas the other core materials increased the fracture toughness under the effect of sea water. Morganti et al [19] have also analyzed the effect of moisture on the dimensional

stability of sandwich composites. It was concluded that moisture and temperature affect the physical behavior of the composite directly by modifying its structural characteristics. Most of these studies are focused on the evaluation of compressive and impact properties [20~25]. Some of the studies pay attention to the evaluation of hygrothermal response and residual strength determination [26~32]. However, the effects of combined temperature-moisture-ionic in the degradation of polymer foam on the performance of sandwich structure have not been fully understood.

The goal of this research is to investigate the effect of moisture on the compressive and flexural properties of PMI foam cored sandwich composites. Due to the presence of ions in sea water, the diffusion rate of water molecules in the sandwich composites may change, leading to a difference water absorption level. After the specimens attained equilibrium stage, the moisture saturated sandwich composites specimens were subjected to compressive test and flexural test. Dry specimens were also tested under the same condition as a comparison to determine the time, temperature, ionic, and moisture dependency of the mechanical behavior. The studies were made not only for the sandwich composite itself, but also for the single components having a closer look at their mesoscopic structure.

II. Experimental

Materials and Sample preparation. The investigated sandwich structures are symmetric. The core consists of the closed cell PMI foam Casecell 75RS (Cashen Advanced Materials Hi-Tech Co,. Ltd). The foam has a density of 75kg/m^3 and a cell diameter of 0.2-0.3mm. The thickness of the foam core is h_c=25mm. The face sheets are made from prepreg fabric of MT300-3K carbon fibers in 602 epoxy resin from an aerospace research institute. The weight of the prepreg fabric is 165g/m^2, with a ply thickness of 0.15mm. Both face sheets are laid up with 7 plies at $[0°/90°/0°/\overline{90°}]_S$ for a total thickness of 1.05mm. J-47C film adhesive is used to bond the core to the face sheets. The sandwich is cured for 2h at135°C and 300kN/m^2 pressure.

Test methods. An ultrasonic inspection of the as-received plate is performed to confirm that the face sheets do not contain area of excessive pores and the face sheets are well bonded to the foam core. The panels are cut into required five specimen dimensions and then tested to obtain static flexural properties and compression properties. Another ultrasonic inspection is performed on the selected random samples to ensure that the cutting operation did not cause any damage. Then the selected samples were then weighed and dried in a vacuum oven at 105°C until their weights stabilized.

The study of moisture absorption followed the ASTM D 5229-92 standard. Procedure “B” is considered suitable for this study. According to this procedure specimens should be immersed in the moist conditions till they reach saturation state. This hygrothermal experiments is conducted at two different temperature, 25°C and 70°C.In addition to that, the tests were taken in DI water and sea water, respectively. Before weighing the specimens, excess surface water was wiped off and specimens reached a state of saturation Criteria specified for saturation state is that the change in weight should be less than 0.1% in 7 days. The percentage mass change of the specimen gain at any time was determined by the

following equation (1)

$$Moisture\quad uptake = \frac{(m_s - m_d)}{m_d} \times 100\,\% \quad (1)$$

where m_s is the mass of specimen after a given immersion time and m_d is the original specimen mass

The flat wise compressive test was performed in accordance with ASTM364 and specimen size in case of flat wise testing was 30×30×27mm. The flat wise compressive strength is calculated using equations (2)

$$FCS = \frac{P}{A} \quad (2)$$

where P is the ultimate load (N) and A is the area of the facing

The flexural strength was measured by the 3-point bending method according to ASTM C 393. The flexural strength of the sandwich construction was calculated by the following equation (3)

$$\sigma_a = \frac{3PL}{2wt^2} \quad (3)$$

where P is the external load at the fracture and t, w and L are the total thickness of the specimen, width and span length, respectively.

III. Results and Discussion

Moisture absorption study. The moisture absorption trends for all the specimens tested in this study are shown in Fig.1. Average values in weight percent are obtained based on moisture absorption by five samples under each type of test condition. As is shown in Fig.1, the moisture absorption at low temperature reaches to equilibrium in about 20 days. However, it takes much longer time at 70°C to attain equilibrium. The sandwich specimens equilibrium was reached in about 30days at higher temperature. The experiments were continued for additional five days after the equilibrium conditions were reached.

Large difference in the moisture absorption tendency is observed with the change in temperature. It is clearly seen that the absorption is 3.00% and 2.70% respectively for low temperature DI water as well as low temperature sea water for PMI foam. While at high temperature water absorption increased to about 2.3 fold for DI water immersed samples and 2.0 fold for sea water at high temperature.

Some general conclusion can be drawn based on Fig.1. First, moisture absorption of specimens immersed in sea water is less than that in DI water, which can be attributed to the presence of salt ionic species in water interferes with the diffusion of water in the sandwich specimens. Moisture penetrates in the composite by diffusion mechanism. Fick's second law of diffusion has been used to study the mechanism of the diffusion behavior since the curves in Figure 1 are linear in the beginning and a plateau at higher immersion times. The diffusion coefficient D is computed using equation (4)

$$D = \pi \frac{l^2}{16}\left[\frac{m_t - m_0}{m_\infty - m_0\sqrt{t}}\right]^2 \quad (4)$$

and is presented in Table 1. Diffusion coefficient depends on the temperature and type of water. Diffusion coefficient increases with temperature and decreases with the ionic species of water. Because ionic species of salt being considerably in size have much slower diffusion rate compared to the diffusion rate of ionic species of DI water. In additional, deposition of salt can take place near the pores in PMI foam which considerably reduces the diffusion rate of water and salt ions in sandwich composites.

Second, the water absorption at room temperature is less than the absorption at high temperature. However, it takes much longer time to attain equilibrium at high temperature. The water molecules move faster at high temperature, this means that higher number of pores is either open or present near the surface. Diffused water accumulates in these pores in the initial stage, leading to a high slop of the curves for the sandwich samples in the beginning of the study. The water absorption of sandwich specimens is difference at high temperature, which can be related to the move rate of water

molecules and the strength of cenospheres. First, the move rate of water molecules at high temperature is much faster than that at room temperature, which makes water molecules accumulated at pores far from the surface. Second, due to the hygrothermal strain gradient in the specimen some of the thin walled cenospheres can fracture making additional space for water to accumulate. In additional, the absorbed water molecules do not react to form chemical bonds with the imide groups, but form physical Van der waals bonds. The effect of the water absorption is a plasticizing of the foam, which gets softer and more ductile. This change in the PMI foam adversely affects the compressive and flexural strength of specimens immersed in high temperature bath compared to the dry specimens.

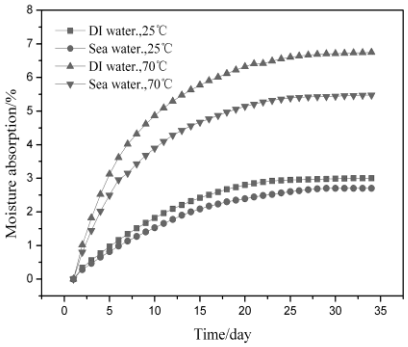


Fig.1 Moisture absorption with exposure time for sandwich composites

Table 1 Maximum moisture absorption, diffusion coefficient for sandwich samples

Sandwich type	M_∞ [%]		Diffusion coefficient [$10^{-6}mm^2/day$]	
	25°C	70°C	25°C	70°C
DI water	3.00	6.75	94.99	238.21
Sea water	2.70	5.48	78.50	200.96

Flatwise Compressive Strength. The flatwise compressive strength of dry and wet samples is shown in Fig.2. No significant difference is observed in the compressive strength of low temperature hydrothermal samples compared to the dry samples. The difference in compressive strength in both cases is less than 5% compared to the dry samples. However, specimens immersed in high temperature water showed much lower values compared to the dry and low temperature specimens. The decrease in compressive strength for high temperature specimens was observed to be 36% and 33% for samples immersed in DI water and sea water, respectively.

Comparison of compressive modulus is shown in Fig.3. It can be seen that modulus of sandwich samples are affected severely due to the presence of moisture. The decrease of the compressive modulus for low temperature DI water and sea water is 49% and 51% respectively. While the decrease in compressive modulus for high temperature specimens is 65% and 68% respectively.

The result can be attributed to two factors, which are the moisture content in the specimen and the property degradation of materials. According to Fig.3 moisture content at low temperature is much less compared to the high temperature samples. Considerable decrease in modulus with slightly change in the compressive strength for low temperature demonstrated that moisture has infiltrated in matrix leading to its plasticization, by which sandwich specimens could be compressed to a high degree of strain without generation any cracks.

Strength as well as modulus have been decreased in high temperature tested specimens. The reason for this may be due to the cenospheres fracture and the plasticization of water. At high temperature the thermal and moisture induced strains generated in the

matrix material some of the cenospheres can be fracture. Due to the fracture of cenospheres, not only the strength and modulus of sandwich composites would go down, but the moisture absorption would also increase. A combined effect of these factors results in reduction of strength and modulus of high temperature hygrothermal sandwich samples. Fig.4 shows evidence of this, where substantial amount of cracks is observed in the sidewalls of the dry specimens. Origination of vertical cracks in a typical fracture features in such materials. These cracks originated due to the brittle nature of the matrix and the effect of secondary tensile stresses in transverse direction. However, wet samples did not show this type of behavior. Behavior of specimens immersed in DI water and salt water was similar. It is observed that PMI core degradation from the high temperature exposure was the major contributing factor in the FCS reduction.

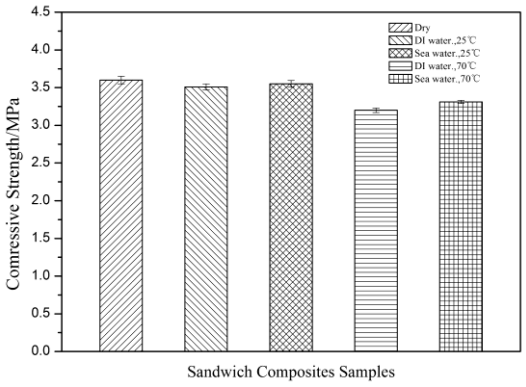


Fig. 2 The FCS of dry and moisture absorbed specimens

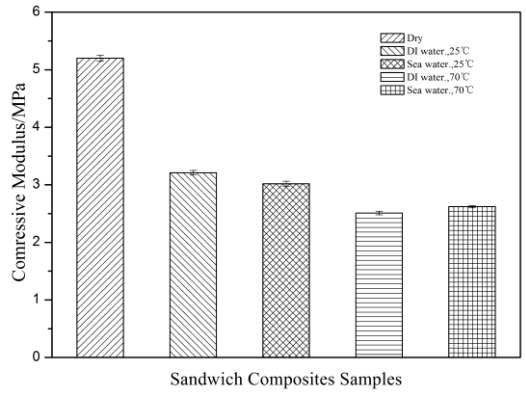
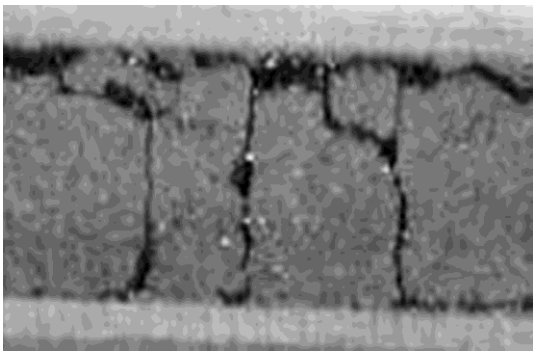
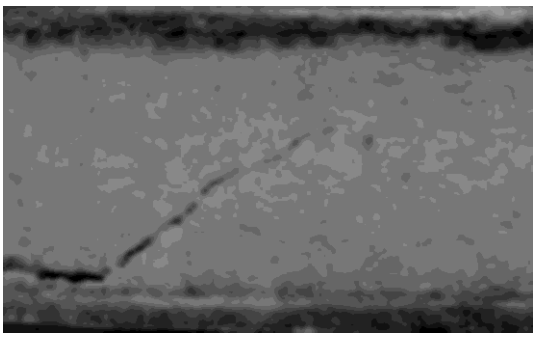


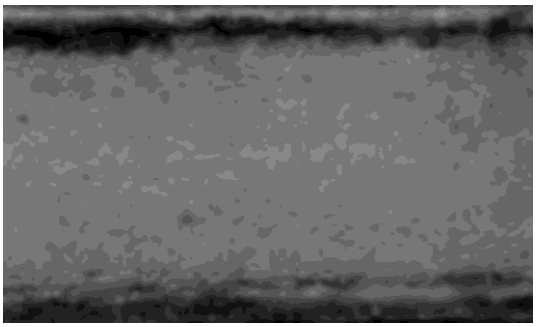
Fig.3 The compressive modulus of dry and moisture absorbed specimens



(a)



(b)



(c)

Fig.4 Photograph of damaged specimens after FCS testing (a) dry samples (b) immersed in 25°C sea water and (c) immersed in 70°C sea water

Flexural Properties. All the composite specimens showed degradation in flexural strength, due to hygrothermal conditioning. The decrease in flexural strength of sandwich composites as a function of operating temperature is shown in Fig.4. For comparison, the flexural properties of dry sandwich composites are also included. Several conclusions can be drawn based on Fig.4. First, Specimens immersed in sea water has higher flexural strength than those immersed in DI water. Because water molecules can plasticizing the PMI foam and has negative effect on the strength of facesheet/core interface. Second. The sandwich composite specimens in high temperature water (both DI water and sea water) exhibited a more remarkable reduce in strength. This result can be attributed to two factors. (a) the PMI water absorption at room temperature is less than that in high temperature; (b) due to the hygrothermal strain gradient value in the specimen at high temperature is much higher than that at low temperature, leading to more thin walled cenosphere fracture which adversely affects the flexure core shear strength.

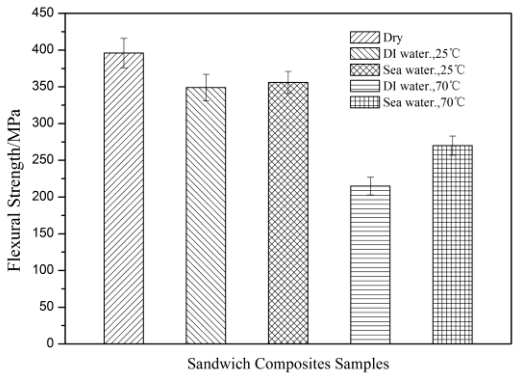


Fig.5 The flexural strengths of dry and moisture absorbed specimens

IV. Conclusion

The following conclusions are summarized based on this study

1. Moisture absorption of specimens was below 5.0% at room temperature. The samples absorbed 6.7% and 5.4% moisture in DI and sea water at the temperature of 70℃, respectively.

2. Considerable decrease in modulus is observed in wet samples compared to the dry samples. The decrease in modulus was 49%, 51%, 65% and 68% respectively for low temperature DI water, low temperature sea water, high temperature DI water and high temperature sea water.

3. No significant difference was observed in the peak compressive strength of low temperature specimens compared to the dry specimens. However, high temperature specimens showed 36% and 33% decrease for samples immersed in DI water and sea water compared to the dry samples.

4. Slightly decrease in flexural strength is seen in low temperature wet samples compared to the dry samples at low temperature. While wet specimens showed 45.7% and 31.8% decrease for samples immersed in DI water and sea water compared to the dry samples at high temperature.

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