Environmental Durability of Banana-Fiber-Reinforced Phenol Formaldehyde Composites

Seena Joseph,[1] Z. Oommen,[2] Sabu Thomas[1]

[1]*School of Chemical Sciences, Mahatma Gandhi University, Priyadarshini Hills (P.O.), Kottayam, Kerala, India*
[2]*Department of Criminal Justice, Albany State University, Albany, Georgia 31705-2796*

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ABSTRACT: We explored the environmental aging behavior of banana-fiber-reinforced phenol formaldehyde (PF) composites. The composites were subjected to water aging, thermal aging, soil burial, and outdoor weathering. The effects of chemical modification and hybridization with glass fibers on the degradability of the composites in different environments were analyzed. The extent of degradation was measured by changes in the weight and tensile properties after aging. Absorbed water increased the weight of water-aged composites, and chemical treatments and hybridization decreased water absorption. The tensile strength and modulus of the banana/PF composites were increased by water aging, whereas the strength and modulus of the glass/PF composites were decreased by water aging. As the glass-fiber loading was increased in the hybrid composites, the increase in strength by water aging was reduced, and at higher glass-fiber loadings, a decrease in strength was observed. The tensile properties of the composites were increased by oven aging. The percentage weight loss was higher for soil-aged samples than for samples weathered outdoors. The weight loss and tensile strength of the glass/PF composites and banana/glass/hybrid/PF composites were much lower than those of the banana/PF composites. Silane treatment, NaOH treatment, and acetylation improved the resistance of the banana/PF composites on outdoor exposure and soil burial. © 2006 Wiley Periodicals, Inc. J Appl Polym Sci 100: 2521–2531, 2006

Key words: ageing; composites; fibers

INTRODUCTION

During the last few decades, ecological concerns have resulted in a renewed interest in natural-fiber composites.[1–6] Natural fibers are environment friendly alternatives to synthetic glass fibers. The advantage of natural fibers over glass fibers is their low cost, biodegradability, renewability, and high specific properties. Glass fibers, on the other hand, are nonrenewable and nondegradable and cause skin irritation and health problems.

A major restriction to the successful use of natural fibers in composite applications is their poor aging and weathering resistance and high moisture absorption. Several studies have been carried out to reduce the water absorption and improve the mechanical properties of composites by chemical modification. Hill and Khalil[7] studied the effect of environmental exposure on the mechanical properties of coir- and oil-palm-fiber-reinforced polyester composites. They found that the mechanical properties of the composites were deteriorated by such exposure and that acetylation and treatment with a silane coupling agent could provide a significant degree of protection.

The principal types of damage that occur to composites are interlaminar cracking, interlayer delamination, fiber breakage, fiber/matrix interface failure, and fiber pullout. All these kinds of damage arise as a result of preexisting technological defects, design features, and events that occur during use. They propagate and interact as a consequence of environmental aging, which leads to the progressive degradation of the properties of the material. Mohd Ishak et al.[8] found that the immersion of rice husk–polypropylene (PP) composites in water resulted in a reduction in tensile properties, the extent of which depended on the water immersion temperature. This was attributed to interfacial degradation and also to microstructural changes in rice husk that reduced its efficiency in acting as a reinforcer. Siddaramiah et al.[9] exposed glass-fiber-reinforced epoxy and unsaturated polyester composites to different aggressive environments, including heat aging, water aging, lubricating oil, fuel, and seawater and obtained a marginal increase in properties with heat aging but a reduction in properties in the other exposed systems.

Singh et al.[10] reported that to minimize the effect of external agents causing the degradation of composites, a hydrophobic morphology should be developed

Correspondence to: S. Thomas (sabut@sancharnet.in or sabut552001@yahoo.com).
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at the fiber matrix interface and resin-rich layer on the outer face of the composites. These were reported to be necessary before use under wet/dry environments. Lin et al.[11] found that the tensile strength of wood-flour-filled PP composites with wood flours of different contents, mesh sizes, and surface treatment increased after immersion in water baths of various temperatures. The contrary was true for flexural strength and modulus when the composites were immersed at 60 and 100°C. Pavlidou and Papaspyrides[12] studied the effect of hygrothermal history on the water absorption and interlaminar shear strength of glass/polyester composites. They found that a strong interface led to matrix-dominated absorption behavior and a weak interface offered an easy path for water penetration through the weak interface. This is called *interface-dominated water absorption*. In the case of silane-treated composites, once water reaches the interface, the siloxane bonds between the silane coupling agent and glass surface are easily hydrolyzed. However, even a small amount of remaining covalent bonds prevents liquids from deteriorating the joint under wet conditions. It has been reported that long-term water exposure of composites fabricated from silane-treated fibers can cause a significant decrease in the mechanical properties. The effects of water on the physicomechanical properties of composites based on low-density polyethylene and linen yarn production waste with and without a coupling agent were studied by Kajaks et al.[13] They found that the introduction of interfacial stearic acid and diphenyl metane diisocyanate modifiers into the system reduced the amount of absorbed water, and the drop in tensile properties was also not very significant.

Hybridization with a stronger and more corrosion resistant synthetic fiber such as glass often improves the aging resistance of natural-fiber composites. The effects of environmental aging on the mechanical properties of bamboo/glass-fiber-reinforced PP hybrid composites were studied by Twe and Liao.[14] Twe and Liao[15] also found that property retention in both bamboo-fiber composites and bamboo/glass hybrid composites with a maliec anhydride modified PP matrix was better than that with PP. They found that hybridizing more durable glass fibers with bamboo fiber was an effective way to improve the durability of natural-fiber composites under environmental aging.

Banana fiber, a waste product of banana cultivation, has been found to be a very good reinforcer in phenolic and polyester resin matrix composites.[16,17] The mechanical properties of banana/phenol formaldehyde (PF) composites were found to be comparable to those of glass fiber/PF composites.[17] The effects of chemical modification on the physical properties of banana fibers were analyzed by our laboratory.[18] The mechanical and dynamic mechanical properties of banana-fiber-reinforced PF composites were improved by chemical treatment.[19] Hybridization with glass fibers increased the properties of the banana fiber/PF composites.[20] Only a few studies have been reported on the effect of different aggressive environments on the properties of natural-fiber composites. In this study, the effects of fiber modification and hybridization on the aging resistance, namely, cold-water, boiling-water, and thermal aging resistance, of the composites were analyzed. The effects of weathering and soil immersion on the mechanical properties of the composites were also analyzed.

EXPERIMENTAL

Materials

A resole-type PF resin obtained from MIS West Coast Polymers Pvt., Ltd. (Kannur, Kerala, India) was used as the matrix. Banana fiber obtained from Sheeba Fibers and Handicrafts (Poovancode, Thamilnadu, India) was used in this study. The chemical constituents of the lignocellulosic banana fiber were cellulose (63–64%), hemicellulose (19%), and lignin (5%) with a moisture content of (10–11%).[21] The glass fiber used was E-Glass Roving, which was obtained from Hitech Fibre Corp. (Bangalore, India).

Fiber modifications

NaOH treatment

Fibers were immersed in a 4% NaOH solution at 27°C for 2 h, washed many times with distilled water, finally washed with water containing little acid, and dried.

Silane treatment

The NaOH-pretreated fibers were dipped in an alcohol/water mixture (60:40) containing triethoxyvinyl silane as a coupling agent at 27°C. The fibers were washed in distilled water and dried.

Heat treatment

The banana fiber was heated at 150°C in an air-circulating oven for 4 h. The fiber was then cooled to room temperature.

Cyanoethylation

The banana fiber was steeped in a 4% solution of NaOH saturated with sodium thiocyanate for 30 min. Subsequently, the fiber was pressed to drain the excess water and removed quickly to a round-bottom flask to react with acrylonitrile (banana fiber/acrylonitrile ratio = 1:3) for 1 h at 40–45°C. After the reaction, a solution of acetic acid was used to neutralize the alkali catalyst. The product was washed well with water and then alcohol.

Acetylation

The NaOH-pretreated fiber was neutralized, washed with water, and air-dried. The fiber was soaked in a 50% solution of acetic acid for 5 min at 27°C, washed, and air-dried.

Latex treatment

We gave the NaOH-pretreated fibers a latex coating by dipping them into a natural rubber latex with a 10% dry rubber content at 27°C.

Preparation of the composites

The fibers were dried to remove moisture before composite preparation. A prepreg route was followed for the preparation of the composites. The hand layup method followed by compression molding was adopted for composite fabrication. Mats of uniform thickness were prepared manually from chopped banana fibers (30 mm) and glass fibers (40 mm). The mats were impregnated in the PF resin, and the prepreg was kept at room temperature up to the semicured stage. It was then pressed at 100°C for 1 h in a mold measuring 150 × 150 × 3 mm to produce a three-dimensionally crosslinked network. Composites of 30% fiber loading were prepared with the fibers. We prepared the hybrid composites by varying the relative volume fractions of fibers (banana/glass fiber volume ratios = 1:0, 0.25:0.75, 0.50:0.50, 0.25:0.75, and 0:1) in the intimate-mix arrangement, where both fibers were intimately mixed, which was also used for preparing the composites. Composites with the glass fiber/banana/glass fiber (GBG) arrangement, that is, with glass fiber at the periphery and banana fiber at the core, were also prepared.

Aging studies

Cold-water aging

Composite samples were cut into specified dimensions according to ASTM D 638-76. They were kept in distilled water at 27°C for 2 weeks to allow them to reach the saturation level. The water adhering to the surface of the composites was wiped off, and the sample was weighed in an electronic balance. The tensile properties of the aged samples were determined.

Thermal aging

Composite samples were cut into specified dimensions according to ASTM D 638-76. They were then placed in an air oven at 100°C for 3 days. The samples were then allowed to cool to room temperature, and tensile testing was carried out.

Boiling water

Samples were kept in boiling water for 2 h. The water adhering to the surface of the composites were wiped off, the sample was weighed in an electronic balance, and tensile testing was carried out.

Soil burial test

Preweighed samples were completely buried in soil with a 50% moisture content. The samples were in constant contact with the soil and buried vertically in jars at a temperature of 27°C. To ensure an adequate supply of oxygen, the lid of jar was not closed, and the moisture content was kept constant. We took the samples out after 12 months, removed the soil with a brush, kept them in an air oven at 50°C for 5 h, and weighed them. The tensile testing of the composite was also done.

Outdoor weathering studies

Weathering evaluation of the composites was carried out to 12 months naturally. For this, the samples were cut into specified dimensions according to ASTM standard for mechanical testing. They was exposed outdoors in the rainfall, solar radiation, and other conditions of the Kerala climate (tropical weather). After 1 year of exposure, the samples were removed, dried in an air oven at 50°C for 5 h, and weighed, and then, tensile testing was carried out.

Tensile testing of the composites

Test specimens were cut from composite sheets. Tensile testing was carried out in a FIE universal tensile testing machine (TNE-500, Fuel Instruments and Engineers, Maharashtra, India) according to ASTM D 638-76. A minimum of six samples were tested in each case, and the average value is reported.

RESULTS AND DISCUSSION

Banana/glass/hybrid composites

Percentage weight change

The percentage weight change in the banana-fiber-reinforced PF composites, glass/PF composites, and banana/glass/hybrid composites after water aging

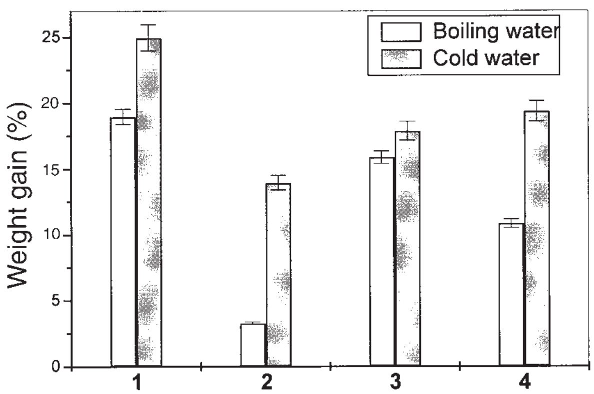

Figure 1 Percentage weight change in the (1) banana-fiber-reinforced PF composites, (2) glass/PF composites, and (3) GBG and (4) intimate-mix banana/glass/hybrid composites after water aging.

are given in Figure 1. Boiling-water and cold-water aging resulted in an increase in weight due to the absorption of water. The percentage weight gain was found to be higher in the banana-fiber composites than in the glass-fiber composites with both boiling-water and cold-water aging. In case of the banana/PF composite, the hydrophilic lignocellulosic banana fiber present in it absorbed water. The penetration of water through the fiber/matrix interface was low in this case because of the strong fiber/matrix interface through chemical interaction, as shown in Figure 2. However, in the glass/PF composites, such a chemical interaction was not possible at the interface, and so water entered into the composite through the interface. The absorption of water by the glass fibers was not considerable, and a very low percentage weight gain was obtained in this case. The percentage weight change of two types of banana/glass/hybrid composites (banana/glass ratio = 70:30), GBG and the other with both fibers intimately mixed was intermediate between those of the banana-fiber and glass-fiber composites. The effect of the hybrid ratio on the percentage weight change in the banana/glass/hybrid composites are shown in Figure 3. It is clear from Figure 3 that the composite containing no glass fiber showed the maximum percentage weight change, and as the glass-fiber loading increased, the percentage weight change also decreased, with the minimum values of percentage weight change present in the glass/PF composite.

Figure 4 shows the effect of air-oven aging on the weight loss percentage of the banana/PF, glass/PF, and banana/glass/hybrid-fiber-reinforced composites with the GBG arrangement and the intimately mixed composites. The weight loss was highest for the banana/PF composites, whereas it was lowest for the glass/PF composites. About 8% weight loss occurred in the banana/PF composites, whereas the weight loss

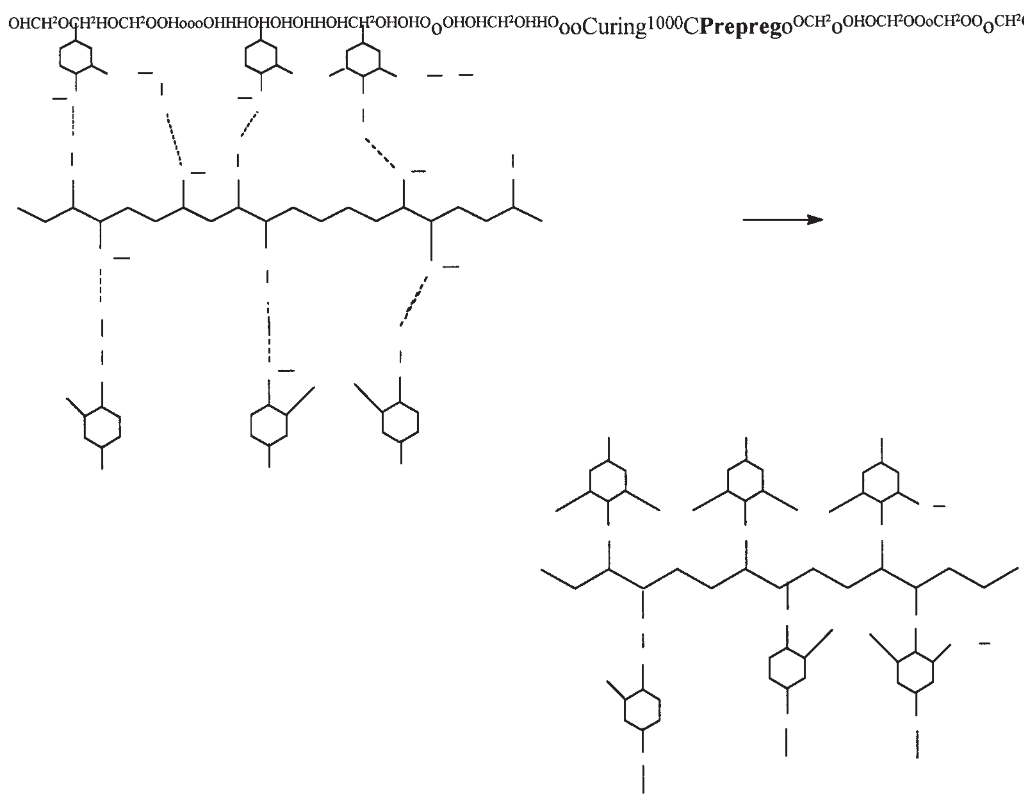

Figure 2 Chemical interaction between the banana fiber and PF resin.

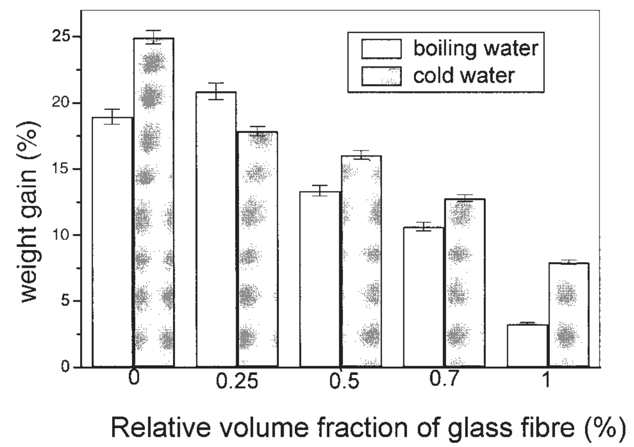

Figure 3 Effect of hybrid ratio on the percentage weight change in the banana/glass/hybrid composites after water aging.

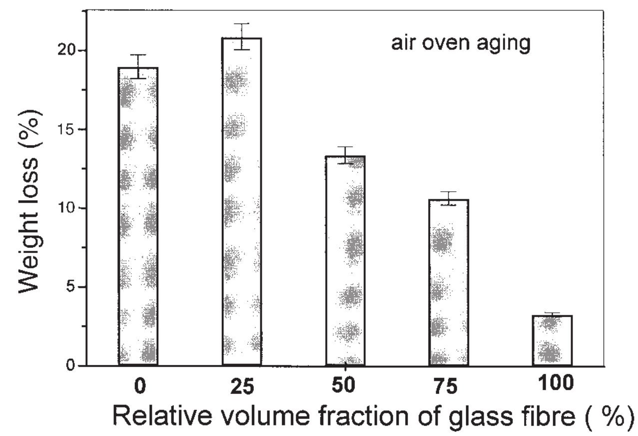

Figure 5 Effect of hybrid ratio on weight loss percentage in the hot-air-oven-aged composites.

was only 3.5% for the glass/PF composites. The loss of weight in the banana/PF composites was associated with removal of moisture and less stable components in the fiber and the moisture entrapped in the microvoids in the composites. In the case of the glass/PF composites, there was no degradation of the glass fiber below 1000°C, so the weight loss was associated with removal of moisture from microvoids and microcracks present in the composite. Similarly, the development of crosslinks at the uncrosslinked cites when present also resulted in the removal of water molecules evolved by the condensation reaction at this temperature. The hybrid composites with two different hybrid designs had lower percentage weight losses than the banana/PF composites. Among the hybrid composites, the intimately mixed composites showed lower values than the GBG arrangement.

The effects of the hybrid ratio on the weight loss percentage after oven aging are shown in Figure 5. It is clear from Figure 5 that the weight loss was highest in the banana-fiber composites, and it decreased with increasing glass-fiber addition. The minimum value of percentage weight loss in the glass/PF composites is due to the higher thermal stability and lesser moisture content in the glass/PF composites than in the banana/PF composites.

Tensile properties

The percentage change in tensile strength, Young's modulus, and elongation values of the banana/PF, glass/PF, and hybrid-fiber-reinforced PF composites after cold-water and boiling-water aging are given in Figures 6, 7, and 8, respectively. The tensile strength and Young's modulus of the banana-fiber-reinforced composites increased with both boiling-water and cold-water aging. Although the increase in modulus for the aged composites was, low there was about a 25% increase in the tensile strength after water immersion. This was due to fact that the absorption of water

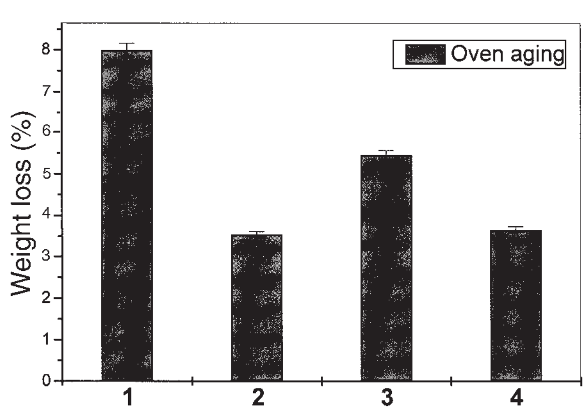

Figure 4 Effect of air-oven aging on the weight loss percentage of the (1) banana/PF, (2) glass/PF, and banana/glass/hybrid-fiber-reinforced composites with (3) GBG and (4) intimate-mix layering patterns.

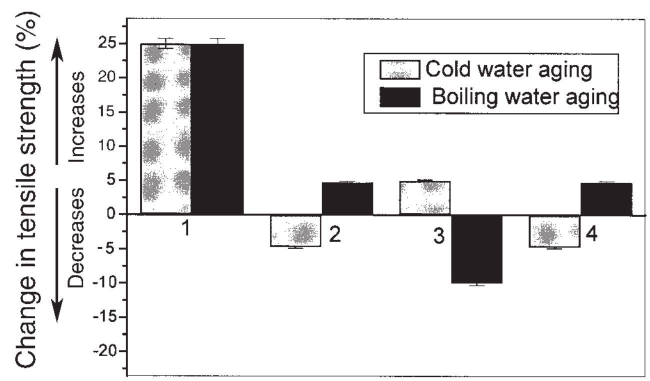

Figure 6 Percentage change in the tensile strength of the (1) banana/PF, (2) glass/PF, and (3) GBG and (4) intimate-mix hybrid-fiber-reinforced PF composites after cold-water and boiling-water aging.

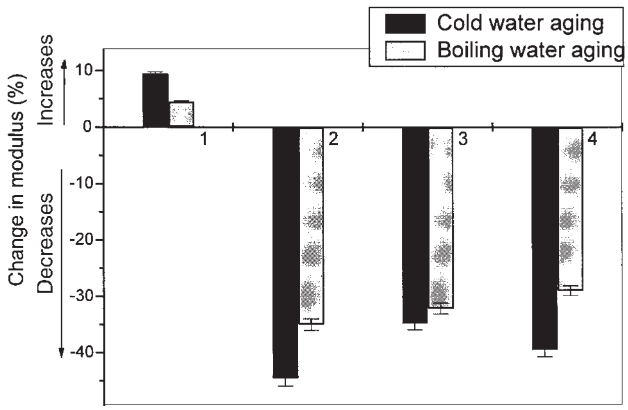

Figure 7 Percentage change in Young's modulus in the (1) banana/PF, (2) glass/PF, and (3) GBG and (4) intimate-mix hybrid-fiber-reinforced PF composites after cold-water and boiling-water aging.

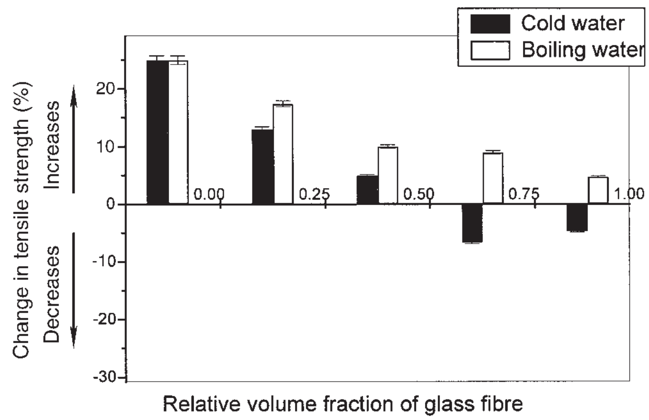

Figure 9 Effect of hybrid ratio on the percentage change in the tensile strength of banana/glass/hybrid composites.

resulted in the swelling of fibers, by which the stress transfer at the fiber/matrix interface was enhanced. The change in tensile strength for the glass/PF composites and hybrid composites with the GBG arrangement and intimate mix were lower than those of the banana/PF composites. About a 5% increase in the tensile strength was obtained for the boiling-water-aged glass/PF composite and the hybrid composite with an intimate mix of the fibers. The tensile strength of the hybrid composite with the GBG arrangement showed about a 9% decrease. The modulus values of the glass/PF composites and hybrid composites decreased with water aging. The elongation at break value also decreased with water aging, except in the cold-water-aged hybrid composite with the GBG arrangement.

The effects of hybrid ratio on the percentage change in the tensile strength, modulus, and elongation at break values of the banana/glass/hybrid composites are given in Figures 9, 10, and 11, respectively. Only the banana fiber/PF composites showed any considerable enhancement in the tensile strength values. As the glass-fiber loading increased in the hybrid composites, the change in strength was reduced, and at higher glass-fiber loadings, a slight decrease in the strength was obtained. In the glass/PF composites, the effect was also less, and a slight decrease in the tensile strength for the cold-water-aged composites and a slight increase in the tensile strength for the hot-water-aged composites were observed. The modulus of the water-aged composites decreased with the incorporation of glass fiber. A slight increase in the modulus was obtained for the banana/PF composites after aging. However, the glass-fiber composites showed a decrease in the modulus, and for the banana/glass/hybrid composites, water aging also resulted in a decrease in the modulus. However, the cold-water-aged hybrid composite with a 0.5 glass-fiber volume ratio and the hot-water-aged hybrid composite with a 0.75 glass-fiber volume ratios showed a slight increase in their modulus values. The elongation value of most of the hybrid composites also decreased with water aging. The effects of hot-air-oven aging on the tensile

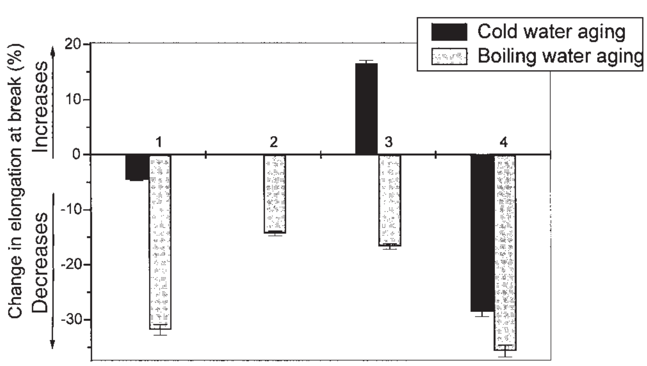

Figure 8 Percentage change in the elongation values of the (1) banana/PF, (2) glass/PF, and (3) GBG and (4) intimate-mix hybrid-fiber-reinforced PF composites after cold-water and boiling-water aging.

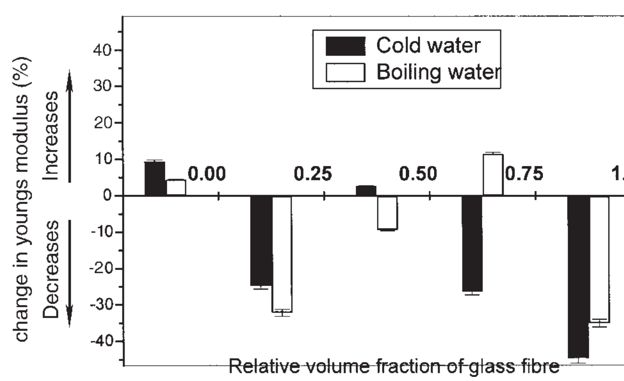

Figure 10 Effect of hybrid ratio on the percentage change in the modulus of banana/glass/hybrid composites.

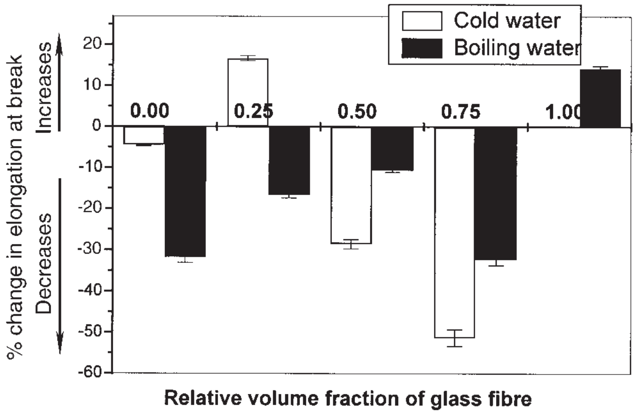

Figure 11 Effect of hybrid ratio on the percentage change in the elongation at break values of banana/glass/hybrid composites.

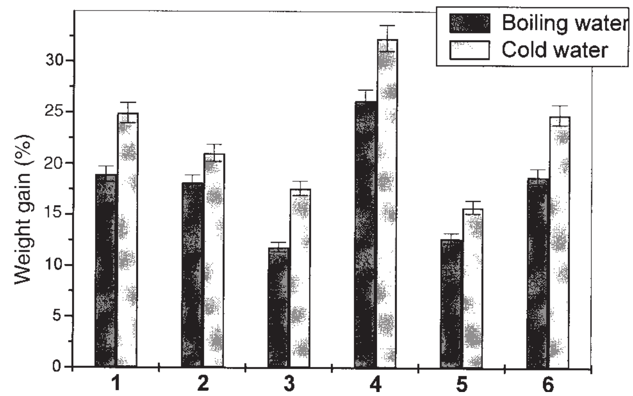

Figure 13 Effect of boiling-water and cold-water aging on the percentage weight gain of the banana-fiber composites after different chemical modifications.

properties of the composites are shown in Figure 12. It is clear from Figure 12 that the tensile strength and modulus values of the composites increased with oven aging. This could be explained by the possible crosslinking of the uncrosslinked sites present in the composites. So there was also a decrease in the elongation values.

Effect of banana-fiber modification

Percentage weight change

The effects of boiling-water and cold-water aging on the percentage weight gain in the banana-fiber composites after different chemical modifications are given in Figure 13. The maximum weight gain was obtained for the banana fiber/PF composites. All of the surface modifications except latex treatment decreased the amount of absorbed water. Cyanoethylation and silane treatment imparted hydrophobicity to the fiber surfaces and thus decreased the amount of absorbed water. Figure 14 shows the percentage weight loss in the hot-air-oven-aged composites. The latex-treated fiber/PF composites showed the maximum weight loss (ca. 10%), whereas the other treatments decreased the weight loss percentage compared to the untreated one. When the fiber was coated with hydrophobic rubber latex, the interface became extremely weak, and this led to increased water uptake.

Tensile properties

The percentage changes in the tensile properties of the treated fiber/PF composites after water aging are shown in Figures 15–17. The tensile strengths of the untreated composites increased with water aging. The percentage increase in the tensile strength of the composites decreased with surface modification, and the boiling-water-aged silane-treated fiber/composite showed a decrease in tensile strength. The modulus of the cyanoethylated and silane-treated fiber/PF com-

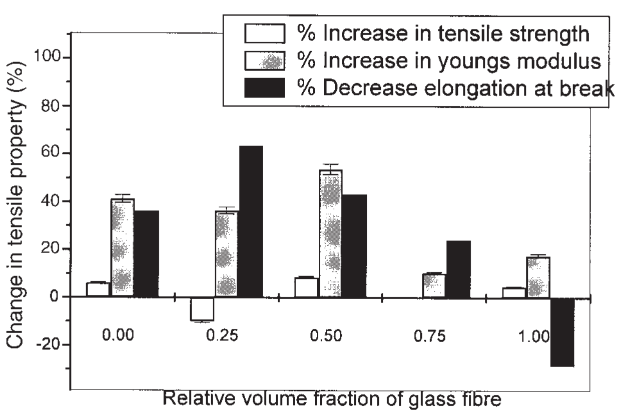

Figure 12 Effect of hot-air-oven aging on the tensile properties of the composites.

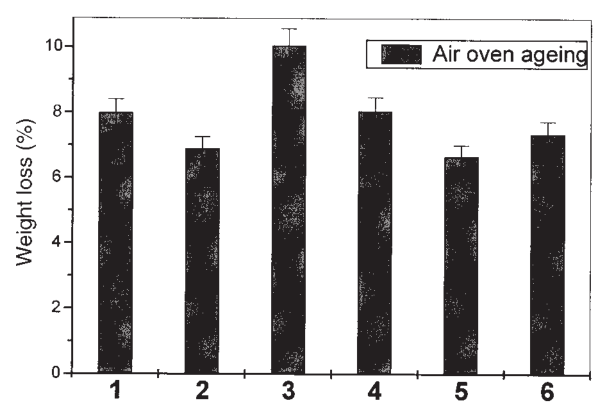

Figure 14 Percentage weight loss in the hot-air-oven-aged composites: (1) untreated, (2) silane-treated, (3) latex-treated, (4) heat-treated, (5) cyanoethylated, and (6) NaOH-treated composites.

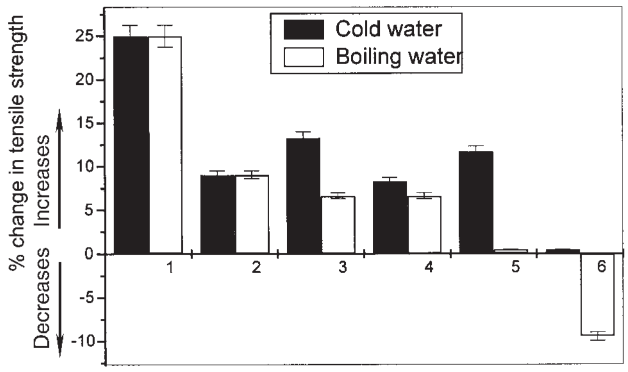

Figure 15 Percentage change in the tensile strength of the fiber/PF composites after water aging: (1) untreated, (2) NaOH-treated, (3) heat-treated, (4) latex-treated, (5) cyanoethylated, and (6) silane-treated composites.

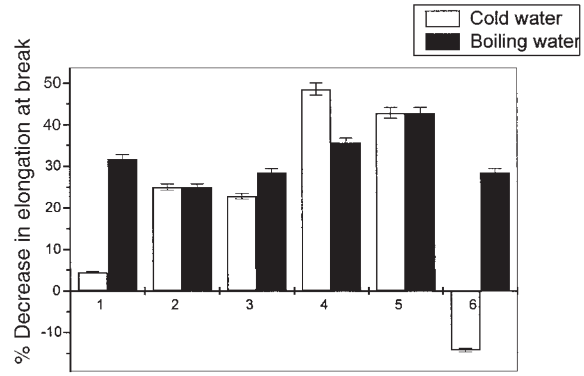

Figure 17 Percentage change in the elongation at break of the fiber/PF composites after water aging: (1) untreated, (2) cyanoethylated, (3) heat-treated, (4) latex-treated, (5) NaOH-treated, and (6) silane-treated composites.

posites decreased after both water agings. The percentage increase in modulus also decreased with the surface modifications. The elongation of the composites decreased with water aging. The percentage decrease in water absorption of the composites increased with surface treatment.

The effects of oven aging on the tensile properties of the modified banana/PF composites are shown in Figure 18. The tensile strength of the composites decreased with oven aging, but the modulus value showed a slight increase after oven aging. This may have been due to the additional crosslinks formed in the composites. The elongation of the composites decreased with aging. So oven aging made the composites more brittle.

Soil burial and outdoor weathering studies

Figure 19 shows the percentage weight loss of the banana/PF, glass/PF, and banana/glass/hybrid fiber/PF composites after 12 months of soil immersion and exposure to natural weathering. It is clear from Figure 19 that the percentage weight loss was higher for soil-buried samples than for the samples subjected to weathering. In the soil-buried samples, the highest weight loss was obtained for the banana/PF composites. This was associated with the biodegradation of the banana fiber in the composite. The weight loss of the glass-fiber composite was much lower compared to that of the banana fiber/PF composites. Hybridization decreased the percentage weight loss of the composites. The hybrid composites with the GBG arrangement had a slightly higher weight loss compared to that with the intimate mix of the fibers. This was because, in the layered composite, interlayer delamination was possible. The microorganisms present could enter into the composite through the interlayer, and degradation of banana fiber occurred, whereas in the intimate mix, the weight loss was very low and was comparable to that of the glass-fiber composites. A similar trend in weight loss was obtained for the weathered composites also, where the percentage weight loss was in the following order: banana/PF > GBG > glass/PF > intimate mix. Here, the intimate

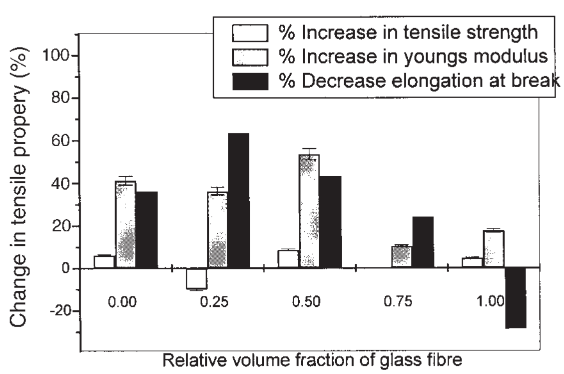

Figure 16 Percentage change in the tensile modulus of the treated fiber/PF composites after water aging.

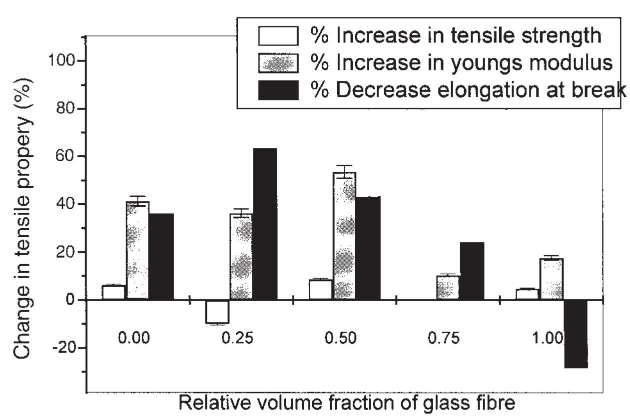

Figure 18 Effect of oven aging on the tensile properties of the modified banana/PF composites.

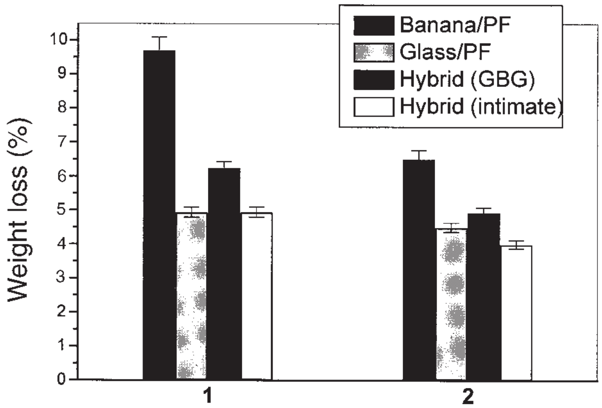

Figure 19 Percentage weight loss in the banana/PF, glass/PF, and banana/glass/hybrid fiber/PF composites after 12 months of (1) soil immersion or (2) exposure to outdoor weathering.

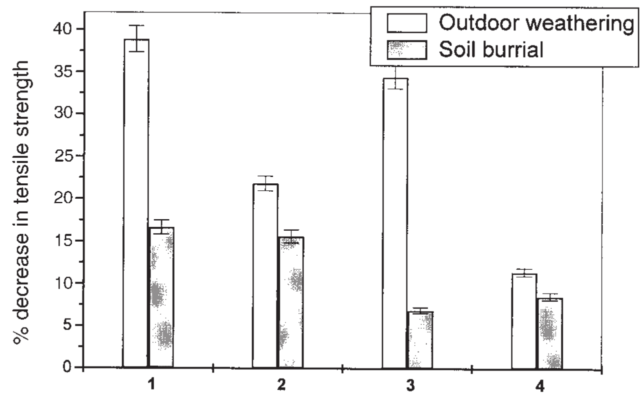

Figure 21 Percentage loss in the tensile strength in the (1) banana/PF, (2) glass/PF, and (3) GBG and (4) intimate-mix hybrid composites after soil burial and outdoor weathering.

mix had the lowest degradation, even lower than that of the glass/PF composite.

The effects of chemical modification of the fiber on the percentage weight loss in the banana/PF composites after soil aging and outdoor weathering are given in Figure 20. As shown in Figure 20, it is clear that the percentage weight loss was lower in the treated fiber/PF composites than in the untreated one. The highest weight loss was obtained for the soil-buried untreated fiber/PF composites, where the possibility for microbial attack was higher. In the latex-treated composite, a high percentage of weight loss was obtained after soil immersion. This was assumed to be due to the biodegradation of natural rubber where microbial attack was possible. Similarly, the poor fiber/matrix interface in the latex-treated fiber made the penetration of microorganisms through the interface, by which the degradation of the fiber occurred, easy. The treatments with NaOH, silane, and acetylation decreased the percentage weight loss in the composites compared to the untreated fiber. This was due to the strong fiber/matrix interface induced by the treatments, which made the composite more stable against microbial attack.

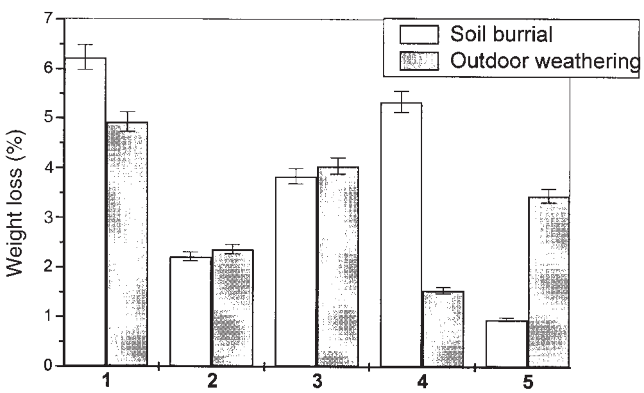

Figure 20 Effect of chemical modification of the fiber on percentage weight loss in the banana/PF composites after soil aging and outdoor weathering: (1) untreated, (2) alkali-treated, (3) silane-treated, (4) latex-treated, and (5) acetylated composites.

The percentage losses in the tensile strength in the banana/PF, glass/PF, and hybrid composites after soil burial and outdoor weathering exposure are given in Figure 21. As in the case of weight loss percentage, the decrease in tensile strength was also highest in the banana/PF composites and lowest in the hybrid composites. The properties of the glass/PF composite did not differ from our expectations, as neither glass fiber nor PF resin is biodegradable. However, the poor fiber/matrix interaction in the glass/PF composite was the reason for the decrease in tensile strength after aging. The hybrid composite with the GBG arrangement had a higher decrease of tensile strength compared to the intimate mix. In the GBG arrangement, the interlayer delamination may have been the reason for this behavior, but this effect was highest in the weathered samples. The intimately mixed fiber/PF composite was the most stable one.

The percentage losses in the modulus of the banana/PF, glass/PF, and hybrid composites after soil burial and outdoor weathering exposure are given in Figure 22. Outdoor weathering considerably affected the modulus of the composites, especially the banana/PF composites, whereas the modulus did not decrease considerably after soil immersion. About a 30% decrease in modulus was observed in the banana/PF composites after outdoor weathering, whereas a slight increase in modulus was obtained after soil immersion. In the glass/PF and hybrid composites, the effect of soil immersion was also low compared to that of outdoor weathering. Both hybrid composites were better than the glass/PF and banana/PF composites in their ability to resist modulus loss with soil burial and outdoor weathering.

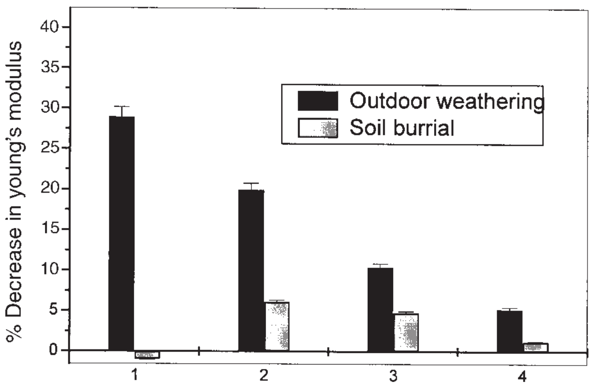

Figure 22 Percentage loss in the Young's modulus in the (1) banana/PF, (2) glass/PF, and (3) GBG and (4) intimate-mix hybrid composites after soil burial and outdoor weathering exposure.

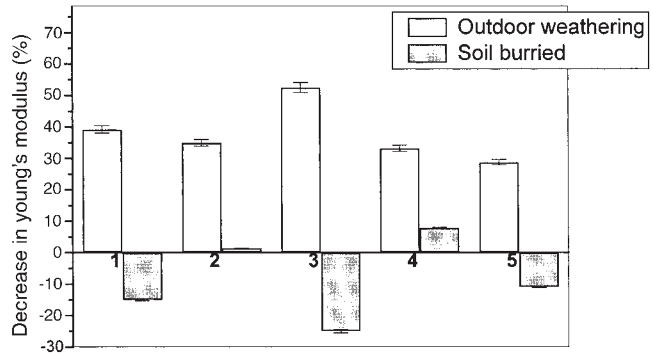

Figure 24 Decrease in the modulus of the treated composites after soil burial and outdoor weathering exposure: (1) untreated, (2) NaOH-treated, (3) latex-treated, (4) silane-treated, and (5) acetylated composites.

The decreases in the tensile properties of the treated fiber/PF composites after soil burial and outdoor weathering exposure are shown in Figure 23. As shown in Figure 23, the highest decrease in tensile strength was obtained for the untreated fiber/PF composites. NaOH treatment and acetylation decreased the percentage loss in the tensile strength with both soil and weathering. The latex-treated composite showed a similar decrease in the tensile strength to that of the untreated fiber/PF composite. However, no considerable change occurred with soil burial. Silane treatment also decreased the degradation of the composite.

The decreases in the moduli of the treated composites after soil burial and outdoor weathering exposure are given in Figure 24. All of the treatments, except the latex treatment, decreased the percentage modulus losses of the composites after outdoor weathering. In the case of untreated, acetylated, and latex-treated composites, a slight increase in modulus occurred after soil burial. No considerable change in modulus was observed for the other composites after soil burial. The elongation at break values of most of the composites decreased with soil immersion and outdoor weathering. The composites that were latex-treated and weathered outdoors, NaOH-treated, and soil-buried and silane-treated showed a slight increase in elongation values.

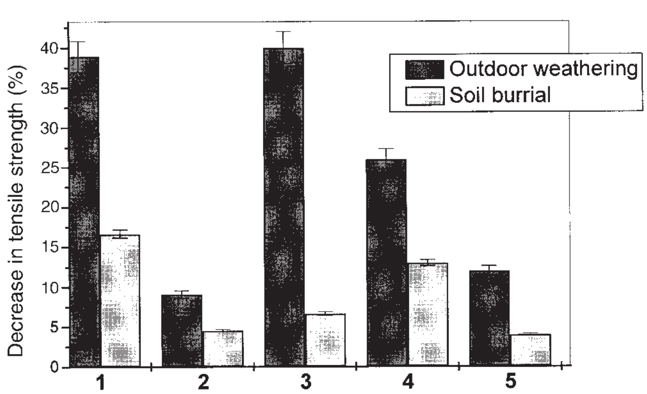

Figure 23 Decrease in the tensile properties of treated fiber/PF composites after soil burial and outdoor weathering exposure: (1) banana/PF, (2) NaOH-treated, (3) latex-treated, (4) silane-treated, and (5) acetylated composites.

CONCLUSIONS

The effects of different aggressive environments on the performance of banana-fiber-reinforced PF composites were evaluated. Weight changes and changes in the tensile properties of the composites on aging were analyzed; we found that water aging increased the weight and tensile properties of the banana/PF composites, whereas this effect was very low for the glass/PF composites. Hot-air-oven aging decreased the weight, whereas the strength and modulus of the composites increased. Hybrid composites of banana fiber and glass fiber were less affected by water and oven aging. All of the surface modifications, except latex treatment, decreased the amount of absorbed water. Cyanoethylation and silane treatment imparted hydrophobicity to the fiber surface and thus decreased the amount of absorbed water. The tensile strength of the composites increased with water aging. The percentage increase in the tensile strength of the composites was decreased by surface modifications. For soil-buried and outdoor-weathered composites, the percentage weight loss was also lower in the treated fiber/PF composites and banana/glass/hybrid/PF composites compared to that of the untreated composite. The highest weight loss was obtained for the soil-buried untreated fiber/PF composites, where the possibility for microbial attack was higher. The treatments with NaOH, silane, and acetylation decreased the percentage weight loss of the composites compared to the untreated composite. Outdoor weathering considerably affected the moduli of the composites, especially the banana/PF composites, whereas the modulus did not decrease considerably after soil immersion. All of the treatments, except the latex treatment, decreased the percentage modulus loss of the composites after outdoor weathering. In the untreated, acetylated, and latex-treated composites, a slight increase in modulus occurred after soil burial.

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