Kenaf Bast Fiber Bundle–Reinforced Unsaturated Polyester Composites. III: Statistical Strength Characteristics and Cost-Performance Analyses

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Abstract

The tensile, flexural, and impact strength distribution and the cost-effectiveness of kenaf bast fiber bundle (KBFB)–reinforced unsaturated polyester composites were studied. Probability models including normal, two-parameter Weibull, gamma, lognormal, exponential, Burr, Pareto, and inverse Gaussian models were fitted against measured composite strengths. Taking the 5th percentile values as the composite's strength design values, the two-parameter Weibull model provided the most conservative composite strength design values. A cost-effectiveness analysis showed these composites were more cost-effective than glass fiber–reinforced sheet molding compounds (SMCs) for carrying tensile and flexural loads when their fiber loadings reached 51.2 and 56.3 percent (wt/wt), respectively. The KBFB-reinforced unsaturated polyester composites were less cost-effective than glass fiber–reinforced SMCs for carrying impact loads. This work suggests that natural fiber–reinforced composites have the potential to be viable replacement materials in applications where impact resistance is not critical.

A high fiber loading kenaf bast fiber bundle (KBFB)–reinforced unsaturated polyester (UPE) composite fabrication process was previously developed (Du et al. 2010). The fabricated KBFB/UPE composites from the process possessed tensile modulus (12.1 GPa), specific modulus (9.92 GPa·cm^3/g), and specific tensile strength (44.8 MPa·cm^3/g) that met specification requirements for glass fiber–reinforced sheet molding compounds (SMCs): 9 GPa, 4.86 GPa·cm^3/g, and 31.4 MPa·cm^3/g, respectively. However, the tensile strengths (54.6 MPa) were slightly lower than the specification requirement (58 MPa) and exhibited large variations. Incorporation of these composites in automotive structural applications remains to be addressed, particularly where reliability in strength values is critical.

A number of statistical models can be used to study the distribution of composite strengths and estimate the reliability of composites. The Weibull distribution model (Weibull 1939) is the most widely used model for characterizing material strength distributions (Weibull 1951, Knight and Hahn 1975, Alqam et al. 2002, Dirikolu

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et al. 2002, Zureick et al. 2006, Rodrigues et al. 2008) and reinforcing fiber strength distributions (Luo and Netravali 1999; Bos et al. 2002; Andersons et al. 2005, 2009; Panthapulakkal et al. 2006; Xue et al. 2009). In addition to the Weibull model, applications of lognormal and gamma distribution models have also been reported (Wu et al. 2006, Basu et al. 2009).

Probability density functions for the two-parameter Weibull, lognormal, and gamma models are given in Equations 1 to 3, respectively. These three models assume that the location parameter is equal to zero.

$$f(x{:}\,\lambda, k) = \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1}\exp\left[-\left(\frac{x}{\lambda}\right)^{k}\right] \quad (1)$$

$$f(x{:}\,\lambda, k) = \frac{1}{\sqrt{2\pi}kx}\exp\left[-\frac{(\ln\ x-\lambda)^2}{2k^2}\right] \quad (2)$$

$$f(x{:}\,\lambda, k) = x^{k-1}\frac{\exp(-x/\lambda)}{\Gamma(k)\lambda^k} \quad (3)$$

where λ and k are scale and shape parameters, respectively. $\Gamma(k)$ is the gamma function defined as

$$\Gamma(k) = \int_0^{+\infty} x^{k-1}e^{-x}\,dx \quad (4)$$

To date, there are no statistical and reliability analysis data available for natural fiber–reinforced thermoset polymer composites. There are a few published articles that study the statistical distribution and reliability of forest products. Guess et al. (2003) statistically studied the internal bond strengths of medium-density fiberboard, but the normal distribution was not suitable. Perhac et al. (2007) studied the probability of wood–plastic composite stiffnesses and flexural strengths using parametric and nonparametric probability plots. Using maleic anhydride grafted polypropylene as a coupling agent did not substantially alter the probability plots. Young et al. (2008) studied the reliability in modulus of elasticity and modulus of rupture for wood–plastic composites and provided three confidence intervals (CIs) for the product's lower percentiles for modulus of elasticity and modulus of rupture using bootstrapping methods. Young et al. (2009) reported that wood strand (raw material for oriented strand board) thicknesses were not normally distributed and the upper percentiles of strand thickness were estimated using bootstrapping methods. Weibull, normal, lognormal, exponential, and a few other quantitative statistical models were used in these studies. Yang et al. (2010) investigated the flexural fatigue behavior of wood flour–polypropylene composites and showed that a nondimensional fatigue model and the two-parameter Weibull probability distribution model could both be used for estimating fatigue life of these wood plastic composites.

Natural fiber–reinforced composites are potentially cost-effective because of their low densities and material costs despite their low absolute strengths. D'Almeida (2001) performed a cost analysis of composites made of sisal, jute, bagasse, and towel gourd fibers. These fibers have strengths ranging from less than 400 MPa to greater than 600 MPa. The cost-effectiveness of their composites for carrying the same flexural load was competitive with glass fiber–reinforced composites for certain fiber strength ranges and fiber volume fractions (percent, vol/vol). Specifically, the natural fiber composites were competitive at 70 percent (vol/vol) fibers with strengths less than 400 MPa, 50 percent (vol/vol) fibers with strengths between 400 and 600 MPa, and 40 percent (vol/vol) fibers with strengths greater than 600 MPa. A cost-effectiveness investigation of the KBFB-reinforced UPE composites prepared in our laboratory (Du et al. 2010) is of interest and highly desirable.

The objectives of this study were (1) to investigate the tensile, flexural, and impact strength statistical distributions and reliability of KBFB-reinforced UPE composites and (2) to analyze the cost-effectiveness of these composites compared with glass fiber–reinforced SMCs for automotive structural component applications.

Materials and Methods

Materials

KBFBs were supplied by Kengro Corporation. The UPE resin (Aropol Q-6585), provided by Ashland Chemical Company, was used as the matrix polymer. The diluent, styrene, and the free radical initiator, *t*-butyl perbenzoate, were purchased from Fisher Scientific Inc. A polyvinyl acetate (PVAc) water emulsion (solid content, 46%), provided by Tailored Chemical Products, Inc., was used as a mat preforming binder.

Composite fabrication

Composites were fabricated as previously described (Du et al. 2010). Long KBFBs were first ground into short fibers with an average length of 3.3 mm. Then, these short KBFBs were preformed into loose mats using the PVAc adhesive, and these preformed mats were infused with predetermined amounts of the UPE resin. The prepreg, assembled by five mats, was then compression molded into composite. The detailed process parameters for the UPE resin formulation, KBFB mat preforming, and compression molding were reported previously. The target fiber loadings were 50 to 60 percent (wt/wt). The composite fiber loadings were calculated after curing and all the squeezed-out resin was sanded off. A total of 25, 44, and 40 specimens were prepared for tensile, flexural, and impact testing, respectively.

Testing

The resultant composite samples were cut to tensile specimens using a CNC machine and were tested on an Instron 5869 universal testing machine under displacement control conditions in accordance with ASTM Standard D638-03 (ASTM International 2004). The cross head rate was set at 4 mm/min, and the tensile strain was recorded by an Instron 2630-100 series extensometer. Flexural test specimens were studied on the same Instron 5869 machine under displacement control conditions in accordance with ASTM Standard D790-03 (ASTM International 2003). The support span was set at 60 mm, and the testing speed was set at 4 mm/min. Impact properties were tested using an Izod fixture on an Instron Dynatup 9250HV Instrumented Drop Tower in accordance with ASTM Standard D256-06 (ASTM International 2006).

Results and Discussion

Statistical distributions

The experimental data analyses were performed using SAS statistical software, release 9.2 (SAS Institute Inc., Cary, North Carolina) and MATLAB 2009a. Table 1 summarizes the descriptive statistics of the measured tensile, flexural, and impact strengths. The experimental data histograms are plotted in Figures 1a, 1b, and 1c for the composites' tensile, flexural, and impact strengths, respectively. The skewness of the tensile strengths distributions is close to zero indicating that the tensile strengths were distributed nearly symmetrically. The skewness values of the flexural and impact strength distributions were −0.234 and −0.287, respectively, indicating the existence of a slightly left skewness. From the flexural and impact strength histograms, one can see the bulk of the flexural and impact strength values lie to the right.

Distribution models including normal, two-parameter Weibull, lognormal, gamma, and several other parametric models were fitted to the experimental data. Seven different statistics of goodness-of-fit for each distribution model for these three strengths were calculated and used as selection criteria. These statistics included −2LogLike, Akaike's information criterion (AIC), corrected Akaike's information criterion (AICC), Schwarz Bayesian information criterion (BIC), Kolmogorov-Smirnov statistic value (KS), Anderson-Darling statistic value (AD), and Cramér-von-Mises statistic value (CvM). The results are summarized in Tables 2, 3, and 4 for tensile, flexural, and impact strengths, respectively. In the tables, the lowest value of a given goodness-of-fit criterion was used to define the optimal distribution model.

The normal distribution model is the best for fitting the experimental tensile strengths (Table 2), followed by the Burr and Weibull distributions. The other six distribution models also show acceptable statistics of fit except the exponential and Pareto distributions. Similar results are observed for flexural strengths (Table 3). The normal distribution model provided the best fit to the measured flexural strengths followed by the inverse Gaussian, lognormal, and Weibull distribution models. The gamma model failed to converge for the given experimental flexural strength data. Hence, no goodness-of-fit statistics are reported for this model. In contrast to tensile and flexural strengths, the Weibull distribution model is the best model for fitting impact strengths (Table 4). The normal distribution ranks just below the Weibull model. These statistics suggest the normal distribution model works best for tensile and flexural strengths, while the Weibull distribution model works best for impact strengths. The exponential and the Pareto models are not appropriate for describing the strength distributions of KBFB-reinforced UPE composites. The remaining distribution models reasonably characterized the strength distributions. The scale and shape parameters and corresponding 95% CIs, based on the maximum likelihood methods, for the optimal distribution models for tensile, flexural, and impact strengths are summarized in Table 5.

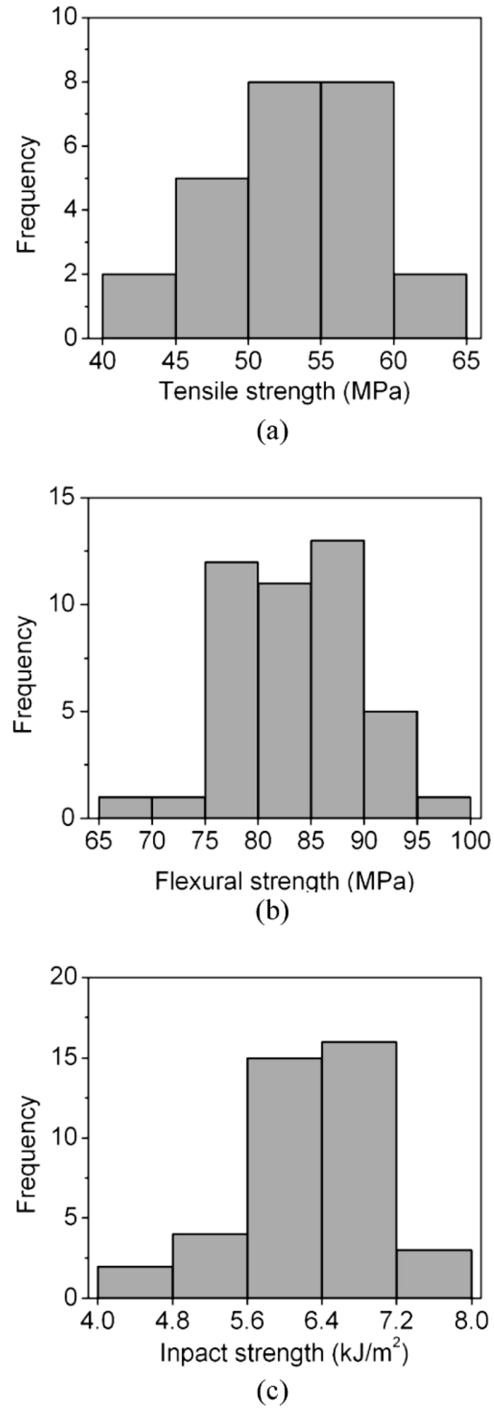

Figure 1.—Histograms of (a) tensile strengths, (b) flexural strengths, and (c) impact strengths of KBFB-reinforced UPE composites.

Table 1.—Statistical summary of tensile, flexural, and impact strengths, respectively.

	Tensile strength (MPa)	Flexural strength (MPa)	Impact strength (kJ/m^2)
Sample size	25	44	40
Fiber loading (wt%)	58–63	62–68	53–63
Mean	53.10	83.64	6.25
SD	5.05	5.67	0.79
COV (%)	9.52	6.78	12.71
Skewness	−0.056	−0.234	−0.287

Table 2.—Goodness-of-fit criteria for each distribution model of the tensile strength data.

Distribution	Fit statistics						
	−2 Log likelihood	AIC	AICC	BIC	KS	AD	CvM
Normal	150.936[a]	154.936[a]	155.481[a]	157.374[a]	0.825	0.359	0.064
Weibull	151.859	155.859	156.404	158.296	0.694[a]	0.388	0.060
Gamma	151.077	155.077	155.622	157.515	0.879	0.384	0.070
Lognormal	151.228	155.228	155.774	157.666	0.905	0.403	0.075
Exponential	248.605	250.605	250.779	251.824	2.857	9.468	2.051
Burr	151.615	157.615	158.758	161.272	0.699	0.347[a]	0.056[a]
Pareto	248.726	252.726	253.272	255.164	2.858	9.472	2.052
Inverse Gaussian	151.215	155.215	155.760	157.653	0.905	0.403	0.075

[a] Indicates the best distribution model.

Table 3.—Goodness-of-fit criteria for each distribution model of the flexural strength data.

Distribution	Fit statistics						
	−2 Log likelihood	AIC	AICC	BIC	KS	AD	CvM
Normal	276.499[a]	280.499[a]	280.792[a]	284.067[a]	0.571	0.237[a]	0.035[a]
Weibull	277.405	281.405	281.698	284.974	0.816	0.378	0.058
Lognormal	277.428	281.428	281.721	284.996	0.482	0.264	0.036
Exponential	477.529	479.529	479.624	481.313	3.779	17.600	3.826
Burr	277.006	283.006	283.606	288.358	0.775	0.315	0.049
Pareto	477.758	481.758	482.051	485.327	3.780	17.606	3.828
Inverse Gaussian	277.429	281.429	281.722	284.997	0.481[a]	0.264	0.036

[a] Indicates the best distribution model.

Table 4.—Goodness-of-fit criteria for each distribution model of the impact strength data.

Distribution	Fit statistics						
	−2 Log likelihood	AIC	AICC	BIC	KS	AD	CvM
Normal	94.051	98.051	98.375	101.429	0.723	0.433	0.058
Weibull	93.816	97.816[a]	98.141[a]	101.194[a]	0.529[a]	0.312[a]	0.045[a]
Gamma	95.301	99.301	99.625	102.679	0.767	0.574	0.076
Lognormal	96.209	100.209	100.534	103.587	0.806	0.665	0.088
Exponential	226.596	228.596	228.701	230.285	3.313	14.047	3.013
Burr	93.412[a]	99.412	100.079	104.479	0.625	0.318	0.048
Pareto	226.657	230.657	230.981	234.035	3.313	14.050	3.014
Inverse Gaussian	96.210	100.210	100.534	103.588	0.808	0.670	0.089

[a] Indicates the best distribution model.

Table 5.—Summary of the best distribution parameters for composite tensile, flexural, and impact strengths, respectively.

	Scale parameter (mean)		Shape parameter (SD)	
	Predicted	95% CI	Predicted	95% CI
Tensile strength (MPa), normal	53.10	51.01–55.18	5.05	3.95–7.03
Flexural strength (MPa), normal	83.64	81.91–85.36	5.67	4.68–7.18
Impact strength (kJ/m^2), Weibull	6.59	6.36–6.83	9.10	7.19–11.52

Reliability analysis and design values

The fitted survival curves for composite tensile, flexural, and impact strengths, based on the relevant optimal distribution models, are plotted in Figures 2a, 2b, and 2c, respectively. The fitted survival curves for all these three strength properties closely matched the nonparametric Kaplan-Meier curves (Kaplan and Meier 1958). The estimated 95% CIs are also included in the figures. The 5th percentile values (95% probability of survival) have normally been chosen as design values in structural engineering (Ellingwood 2000). Table 6 summarizes the 5th percentile values estimated by the best distribution model (normal distribution for tensile and flexural strengths, and Weibull distribution for impact strengths). The values of

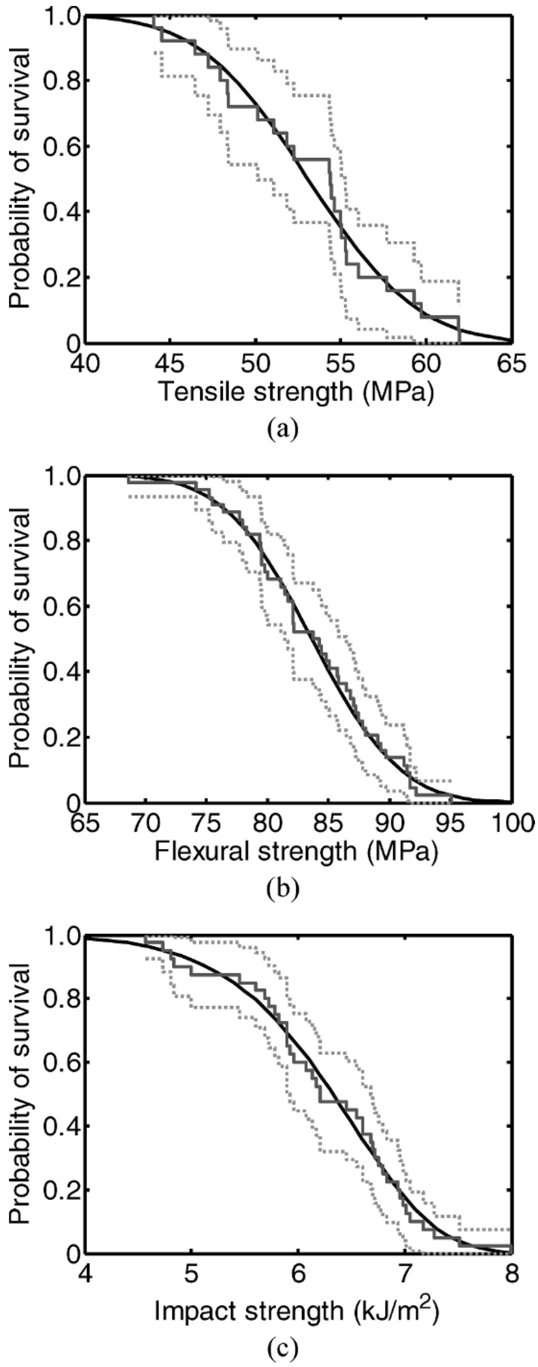

Figure 2.—The best distribution model fitted survival curves from the experimental (a) tensile, (b) flexural, and (c) impact strengths of KBFB-reinforced UPE composites with the nonparametric Kaplan-Meier survival curves (solid line) with 95% CIs (dashed line).

the normal 5th percentile tensile and flexural strengths were 44.95 and 74.42 MPa, respectively. One can see that the normal 5th percentile tensile strength value was higher than the corresponding experimental tensile strength (44.50 MPa), which is not acceptable where a conservative estimate of strength is desired. However, values of the Weibull 5th percentile tensile and flexural strengths (43.15 MPa, 72.24 MPa) were both lower than the experimental data. Therefore, though the normal distribution model was the best fitting model for tensile and flexural strengths, the Weibull distribution model provided the most conservative strength estimates. The value of the Weibull 5th percentile impact strength was 4.75 kJ/m^2, which closely matched the experimental data (4.77 kJ/m^2). Again, the normal distribution model provided a nonconservative 5th percentile impact strength value.

The conservative strengths obtained using the Weibull distribution model are consistent with results reported by Kam and Chang (1997) and Alqam et al. (2002). The estimated 5th percentile tensile, flexural, and impact strength values in this study using the Weibull distribution model, can be used as design strength allowable for the KBFB-reinforced UPE composites considered here. Based on this study, 95 percent of these laboratory-manufactured KBFB-reinforced UPE composites will conservatively survive when the tensile stress, flexural stress, and applied impact energy per square meter are lower than 43.15 MPa, 72.24 MPa, and 4.75 kJ/m^2, respectively. As part of future work, an investigation on the effect of sample size on the design strengths may be desirable.

Cost analysis

Although possessing lower absolute strengths, natural fiber–reinforced composite materials can compete with glass fiber–reinforced composites in terms of specific properties and costs. D'Almeida (2001) proposed a cost analysis model to calculate the price per unit length of a composite specimen, Q, subjected to an applied three-point bending load P.

$$Q = \frac{3}{2}\frac{L}{t}\frac{\rho_C}{\sigma_C}X_C P \tag{5}$$

In this equation, L and t are the test span and the specimen thickness, ρ_C and σ_C are the composite density and flexural strength, and X_C is the price per unit of composite weight. Equation 5 can also be written as

$$Q = \beta \cdot P \tag{6}$$

$$\beta = \frac{3}{2}\frac{L}{t}\frac{\rho_C}{\sigma_C}X_C \tag{7}$$

Here, the cost parameter β is a constant for a given composite geometry.

Similarly, the price per unit length of a composite tensile specimen can be calculated.

$$Q = \frac{\rho_C}{\sigma_{\text{C-Tension}}}X_C P \tag{8}$$

or

$$Q = \beta \cdot P \tag{9}$$

$$\beta = \frac{\rho_C}{\sigma_{\text{C-Tension}}}X_C \tag{10}$$

Here, $\sigma_{\text{C-Tension}}$ is the composite tensile strength. The cost parameter β for a composite subjected to a tensile load is independent of the composite's geometry.

In the same manner, the price per unit length of a composite can be calculated for the material subjected to impact loads.

Table 6.—Fifth percentile values (95% probability of survival) for composite tensile, flexural, and impact strengths, respectively.

	5th percentile value				
		Normal		Weibull	
	Experimental	Estimate	95% CI	Estimate[a]	95% CI
Tensile strength (MPa)	44.50	44.95	41.97–47.92	43.15	39.35–47.31
Flexural strength (MPa)	75.19	74.42	71.88–76.96	72.24	68.77–75.88
Impact strength (kJ/m^2)	4.77	4.96	4.59–5.33	4.75	4.32–5.23

[a] The Weibull estimates were statistically significantly lower than the normal estimates.

$$Q = \frac{\rho_C}{I_C} X_C E \quad (11)$$

or

$$Q = \beta \cdot E \quad (12)$$

$$\beta = \frac{\rho_C}{I_C} X_C \quad (13)$$

In Equations 12 and 13, E is the absorbed energy and I_C is the composite impact strength.

The composite with a lower value of the parameter β will be more cost-effective to carry the same load or to resist the same amount of impact energy. A cost-effectiveness coefficient K is proposed to compare kenaf fiber–reinforced UPE composites with a type of commercial glass fiber–reinforced SMC-R25 of each type of load,

$$K = \frac{\beta_C}{\beta_{SMC}} \quad (14)$$

Here, β_C and β_{SMC} are the cost parameters for the KBFB-reinforced composite and the glass fiber–reinforced SMC. The cost-effectiveness coefficients of kenaf fiber–reinforced UPE composites subjected to tensile (K_T), flexural (K_F), and impact loads (K_I) can be calculated by Equations 15 to 17.

$$K_T = \frac{(\rho_C/\sigma_{C\text{-Tension}}) \cdot X_C}{(\rho_{SMC}/\sigma_{SMC\text{-Tension}}) \cdot X_{SMC}} \quad (15)$$

$$K_F = \frac{(\rho_C/\sigma_{C\text{-Flexure}}) \cdot X_C}{(\rho_{SMC}/\sigma_{SMC\text{-Flexure}}) \cdot X_{SMC}} \quad (16)$$

$$K_I = \frac{(\rho_C/I_C) \cdot X_C}{(\rho_{SMC}/I_{SMC}) \cdot X_{SMC}} \quad (17)$$

In these equations, ρ_{SMC}, $\sigma_{SMC\text{-Tension}}$, $\sigma_{SMC\text{-Flexure}}$, and I_{SMC} are density, tensile strength, flexural strength, and impact resistance for glass fiber–reinforced SMC, respectively. When a KBFB-reinforced composite is more cost-effective than the glass fiber–reinforced SMC, then the corresponding cost-effective coefficient is less than 1. The price per unit weight of SMC-R25, X_{SMC}, is determined at the 25 percent fiber loading. The price per unit composite weight, X_C, at various fiber loadings can be calculated by Equation 18:

$$X_C = x_{UPE} \cdot wt_{UPE}\% + x_{PVAc} \cdot wt_{PVAc}\% + x_{KBFB} \cdot wt_{KBFB}\% \quad (18)$$

Here, x and wt% are the unit price and weight percentage for each component.

Table 7 summarizes the price of each constituent in the kenaf fiber–reinforced composite and in a typical glass fiber–reinforced SMC (R25 SMC). Prices of UPE and filler for SMC were obtained from an automotive component manufacturer. The weight percentage of each component, as well as tensile, flexural, and impact strengths of R25 SMCs are listed in Table 7. These data were used to calculate the cost-effectiveness coefficients of kenaf fiber–reinforced composites for comparison to glass fiber–reinforced R25 SMCs. The cost coefficients K_T, K_F, and K_I are plotted in Figures 3a, 3b, and 3c against fiber loadings for tensile, flexural, and impact loads, respectively.

In general, these coefficients decrease, i.e., KBFB composites become more cost-effective, with increasing fiber loading. KBFB-reinforced composites become more cost-effective than glass fiber–reinforced SMCs for tensile and flexural applications when the fiber loading exceeds 51.2 and 56.3 percent (wt/wt), respectively. These observations suggest kenaf fiber–reinforced composites are viable candidate replacement materials for glass fiber–reinforced

Table 7.—The component prices, densities, and mechanical properties of KBFB and glass fiber–reinforced UPE composites.

Material	Unit price and properties	Source
KBFB-reinforced composites		
Price (US$/kg)		
Kenaf fiber	0.44–0.55	Zampaloni et al. 2007
UPE	2.65	
PVAc	1.30	Manufacturer
Composite cost (US$/kg)	1.03	
Density (g/cm^3)	1.2	
SMC (R25)		
Price (US$/kg)		
E-glass fiber (25%)	3.25	Mohanty et al. 2000
UPE (25%)	2.65	
Filler (50%)	0.22	
Composite cost (US$/kg)	1.59	
Density (g/cm^3)	1.85	European Alliance for SMC 2001
Tensile strength (MPa)	73	European Alliance for SMC 2001
Flexural strength (MPa)	178	European Alliance for SMC 2001
Impact (kJ/m^2)	75	European Alliance for SMC 2001

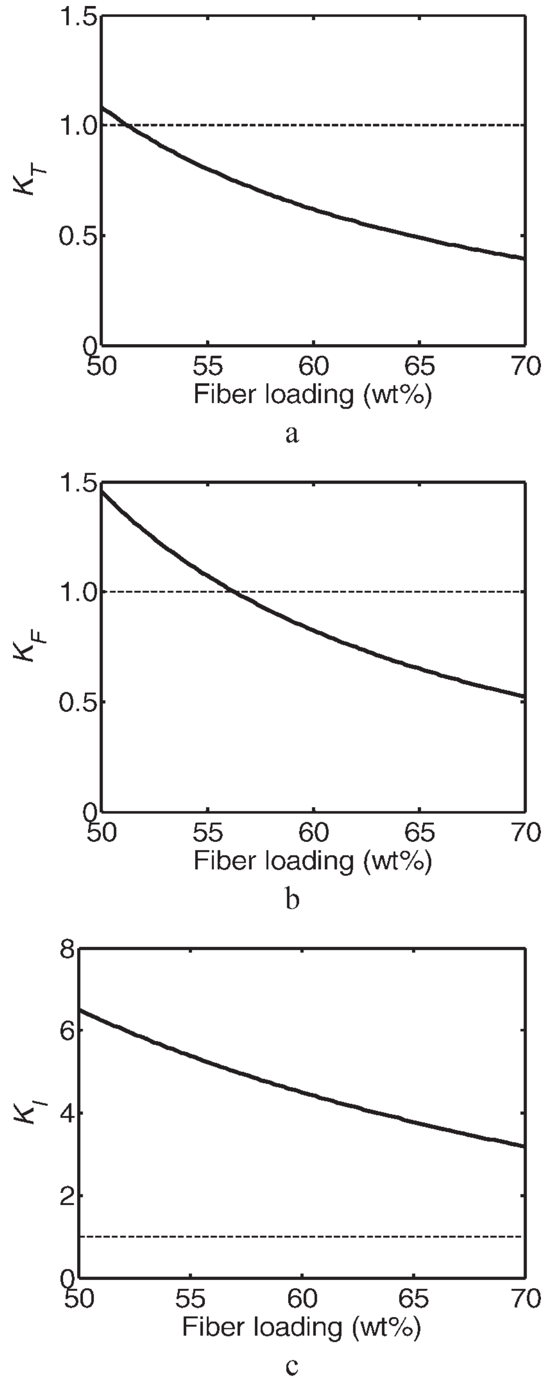

Figure 3.—Cost coefficients, K_T, K_F, and K_I, of KBFB-reinforced UPE composites for carrying (a) tensile loads, (b) flexural loads, and (c) impact loads.

SMCs that carry tensile or flexural loads, within the fiber weight fraction range from 50 to 70 percent (wt/wt).

KBFB-reinforced composites were less cost-effective than glass fiber–reinforced SMCs subjected to impact loads. The cost coefficient K_I for composites carrying impact loads is always substantially higher than 1, although this coefficient decreased from 6.50 to 3.19 as the fiber weight percentage increased from 50 to 70 percent. This might be attributed to energy absorption due to the distributed brittle fracture of the glass fibers; KBFBs have no similar energy dissipation mechanism. Thus, kenaf fiber–reinforced composites appear to be less cost-effective than glass fiber–reinforced SMCs for carrying impact loads.

Summary and Conclusions

The KBFB-reinforced UPE composite tensile, flexural, and impact strengths were studied statistically based on experimental results. The normal and two-parameter Weibull models were found to appropriately describe the distribution of the composite strengths. Other distribution models, gamma, lognormal, Burr, and Inverse Gaussian, provided reasonable characterization of composite strengths, with the exception of the exponential and Pareto models. The two-parameter Weibull model provided the most conservative 5th percentile design values for composite tensile, flexural, and impact strengths (43.15 MPa, 72.24 MPa, and 4.75 kJ/m^2, respectively). These values can be used as design strength allowable for KBFB-reinforced UPE composites.

The cost-effectiveness analysis suggested that KBFB-reinforced UPE composites were more cost-effective than glass fiber–reinforced SMCs for carrying tensile and flexural loads when their fiber loadings were higher than 51.24 and 56.29 percent (wt/wt), respectively. However, at these fiber loading levels, this class of composites were less cost-effective than glass fiber–reinforced SMCs for impact resistance applications.

Acknowledgments

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