PHYSICAL AND MECHANICAL PROPERTIES OF VENEER–POLYURETHANE FOAM COMPOSITES

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Abstract. The purpose of this study was to develop core composite materials using veneer residues combined with appropriate matrix material. This study describes the evaluation processes of physical and mechanical properties of a recently developed polyurethane–veneer composite. In the layered construction of the product, the veneers provide strength and stiffness, whereas the polyurethane foam has a lateral supporting effect and sets the final dimensions in thickness of the slabs. Two key properties were studied. First, the density in relation to the wood constituent's moisture content and ambient RH was analyzed by three-level, two-factor, robust parametric design ($\boldsymbol{3^{II}}$ RPD). Also, a two-level, three-factor + center point experimental design ($\boldsymbol{2^{III}} + \boldsymbol{C_p}$) helped to evaluate the effects of the selected parameters on compression strength. Standard test results confirmed the improved compression force resistance compared with foams without reinforcement, whereas the density of the new composite remained way below the densities of core materials currently on the market. The intended use of the developed composite includes carrier substrates for countertops, interior door leaves, indoor heat insulating, and acoustic insulation panels as well as structural insulated panels.

Keywords: Composite, veneer, polyurethane foam, moisture, strength, MOE, RPD.

INTRODUCTION

Both the furniture and the construction industries are seeking lightweight composite panels with adequate strength and stiffness. Besides the advantage of high strength-to-weight ratio, these panels should provide some fastener holding capacity and allow easy applications on the assembly sites. Furthermore, the decreased transportation costs and special features such as designed heat and sound insulation characteristics should make these low-density products more profitable. Sandwich beams and panels are basically formed from two thin and stiff sheets, so-called faces, separated by a thick, light, and weaker core. The higher quality facades should resist bending stresses effectively, whereas the core has to provide adequate shear resistance through the cross-section and at the interface of the layers. Thus, bending under load, shear failure, and delamination may be avoided. A vast variety of so-called sandwich panels have been developed in the past. Also, significant diversity exists in core materials that are currently on the market.

Commonly used nonmetallic face substances include solid wood in the form of veneers or decorative laminates over carriers of particle and fiber composites. Face materials for structural composites include plywood, oriented strandboard, and sheetrock panels. Cores can be divided into four main groups: corrugated panels, honeycomb, solid wood such as balsa (*Ochroma pyramidale*), and foams. The last core material offers greater shear strength and stiffness-to-weight ratios of the composite sandwich compared with panels having paper honeycomb cores (Zenkert 1997). However, the shear and compression force resistance of currently used foams are significantly less than that of solid wood, particleboard, or medium-density fiberboard. One of the solutions to improve shear

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and compression properties of foam-based cores is their reinforcement with lightweight but stiff and strong materials. The aim of this comprehensive study was to develop a versatile, foam-based core material reinforced with thin veneer strips. Manipulation of density and orientation of reinforcements provide possibilities to better engineer cores of sandwich panels for various applications. Research results confirmed the viability of reinforcement of polyurethane (PUR) matrix materials with veneer strips (Denes et al 2006; Lang and Denes 2007). The second phase of this study dealt with the evaluation of most critical physical and mechanical properties, namely the optimization of density and compression strength. The results of these studies are summarized here.

MATERIALS AND METHODS

Product and Specimen Preparations

Decorative veneers, 0.7-1.0 mm thick after slicing, underwent side-clipping to create rectangular-shaped veneer sheets in a bundle. This operation resulted in clippings 4-6 m long and 20-60 mm wide. Also, a significant volume of veneers may be rejected because of aesthetic and/or quality reasons. These residues combined with appropriate matrix material can be converted to low-density, reinforced slabs. The slabs may be further manipulated to achieve specific attributes in sandwich panels for various applications.

This research used three dominant North American species, namely black cherry (*Prunus serotina*), red oak (*Quercus rubra* spp.), and maple (*Acer* spp.) veneer clippings, as reinforcing elements in the composite. The clippings were obtained from industrial manufacturers located in the Appalachian region (West Virginia and Pennsylvania). A moisture curing, one-component PUR foam–adhesive matrix material, applied to the veneers, formulated the slabs. The fully set polymeric diisocyanate-based foam was semirigid and predominantly close celled with good adhesion to wood. Table 1 lists the principal physical and mechanical properties of the cured PUR foam.

Table 1. Properties of the applied polyurethane foam.

Density	kg/m^{-3}	23
Dimensional stability	%	≤10
Tensile strength	kPa	70
Compressive strength	kPa	60
Shear strength	kPa	40

A laboratory-scale roller coater applied the PUR to the veneer strips. The spread of the matrix was regulated by the rotational speed of the rollers and by the distance between them. The covered veneer strips were manually formed into a mat on aluminum caul plates with approximately 0.7- × 0.7-m in-plane dimensions. The alignment of veneer strips in each layer was always unidirectional (ie clippings or veneer strands were aligned in the same direction). The contact heat applications happened through a single daylight press with the same platen dimensions as the caul plates. The density and slab thickness could be controlled in several ways. The experimental designs used the parameters that influence densities and thicknesses; thus, they are discussed in the corresponding experimental sections. Figure 1 shows the edge view of the relatively low- and high-density slabs. The slabs were ripped or cross-cut into 50-mm strips that were further processed to form specimens (50 × 50 × 50 mm) for density and compression strength evaluations.

The formation and cure of the PUR foams are triggered by the moisture content of the substrate and/or the ambient RH. Additional factors may include consolidation pressure and ambient and substrate temperature. The applied thickness of the matrix (spread of the PUR) is also a deterministic element in development of the final density and thickness. These interacting and occasionally hard to control factors make the experimental designs complicated. Therefore, to separate the effects of material- and technology-controlled parameters, the investigation was split into two segments. The first part dealt with the factorial impacts of moisture content and RH. The second phase investigated the effects of more controllable technological parameters such as

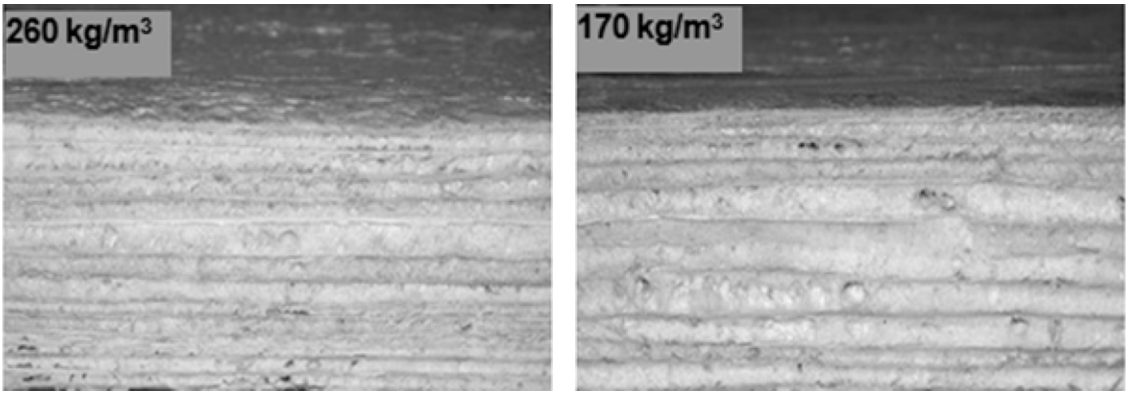

Figure 1. High- and medium-density polyurethane–veneer composites.

spread of matrix, consolidation pressure, and curing temperature.

Experimental Design and Preparations

Phase I. This segment of the investigation used northern red oak rejected veneer sheets and commercially available PUR foam matrix. The selected experimental factors were the moisture content of veneer constituents and the ambient RH. Three levels of each factor represented the treatments as follows: veneer moisture contents of 4, 10, and 16% and ambient relative humidities of 50, 65, and 80%. Establishing the veneer moisture contents and ensuring the ambient RH for the foam cure took place in a walk-in conditioning chamber. Other parameters were set to constant during the entire first phase with the matrix spread of 135 g/m^2. The curing occurred at room temperature of 20 ± 1°C under 0.15-kPa consolidation pressure. After 24 h of hardening, the slabs were removed from the preset environments and further converted to cube-shaped density and compression test specimens.

Phase II. During the second phase, the effects of more controllable technological parameters were analyzed. Table 2 contains the description of factors and their levels. These correspond to a two-level, three-factor + center point experimental design ($2^{III} + C_p$). The specimen manufacturing for this phase included the mixture of Appalachian hardwood veneer side clippings conditioned to ≈12% MC. The proportions of the individual species were about 60% cherry, 35% red oak, and 5% maple. The same PUR matrix material was applied and a digital scale, with precision of ±0.01 g, helped to assess the spread of matrix (resin). The composite mats were formed on caul plates at indoor environmental conditions and placed in the press, which was set for the desired cure temperature and pressure. Similarly, after 24 h of curing time, the specimen formation began.

Testing methods. Density measurements followed the specifications of the relevant ASTM standard (ASTM 1996a). Dimensions were assessed at two locations at the edges and at the four corners for thickness. Data were then averaged to compute the volume and the appropriate cross-sectional areas, followed by mass measurements with ±0.01-g precision.

Compression tests were performed on an MTS (Eden Prairie, MN) servo-hydraulic universal machine equipped with a 10-kN ± 1-N load cell. Load application occurred through a self-aligning block placed underneath the specimens (Fig 2). Standard testing regulations (ASTM

Table 2. Experimental factors and their levels of Phase II.

	Factors		Factor levels	
Symbol	Description	Unit	–1	+1
A	Resin content	g/m^2	100	170
B	Pressure	kPa	6.9	55.2
C	Temperature	°C	25	80

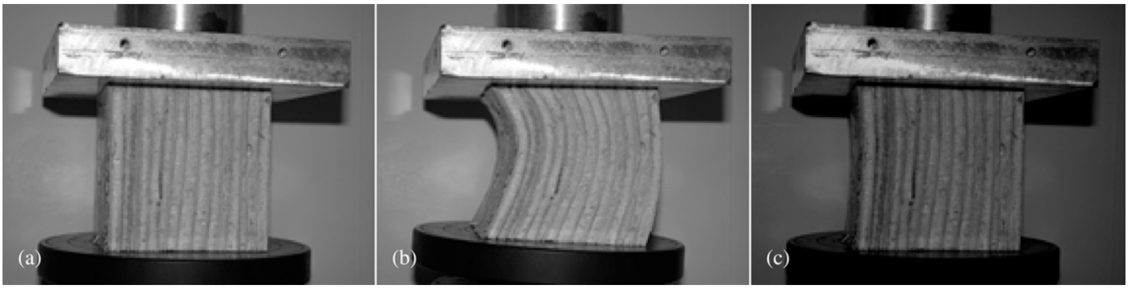

Figure 2. Experimental setup of the compression strength measurements (a) before loading, (b) at maximum load, and (c) at relaxation after unloading.

1996b) were applied except for the specimens that were 50 × 50 × 50 mm. Compression strength appraisal took place in two directions relative to the strand alignment. In the first series, load was applied parallel to the strands' grains. During the second series, the grain was aligned perpendicular to the load direction (edge loading). No specimens with flatwise strands were tested. Furthermore, because of the complex deformation (ie buckling, torsion, and compression), the determination of modulus of elasticity in compression was not feasible.

Analytical procedures. Generally, the optimization of a product or processes means to identify the key variables that influence the quality characteristics of the final product. These factors may be deterministic and are usually controllable. However, some of these variables are fully or partially stochastic. These so-called noise factors are beyond control. After selecting the control and noise factors that affect the quality characteristics of the product, an appropriate experimental matrix is developed according to the orthogonal design generation rules (Adler et al 1977). Data processing begins with the analysis of variance to determine the significance of factors and interactions. The model parameters should be quantified using regression analysis. Predicted response values, generated by the obtained regression model, then can be represented as response surfaces and the optimal region or optimization direction (by steepest ascent) can be identified or assigned. The robust parametric design (RPD) of experiments has been discussed in several publications (Taguchi 1987; Nair et al 1992; Montgomery 1997, 1999, 2005; Denes et al 2006). The interested reader may obtain more in-depth information about the RPD procedure from the literature.

RESULTS AND DISCUSSION

Phase I: Effects of Ambient RH and Moisture Content on Density

The overall effects of RH and moisture content may be studied from Fig 3. As shown by the 3-D mesh, the increase of ambient RH resulted in a density increase for all levels of strand moisture contents. The mesh of this 3-D diagram was interpolated using the inverse

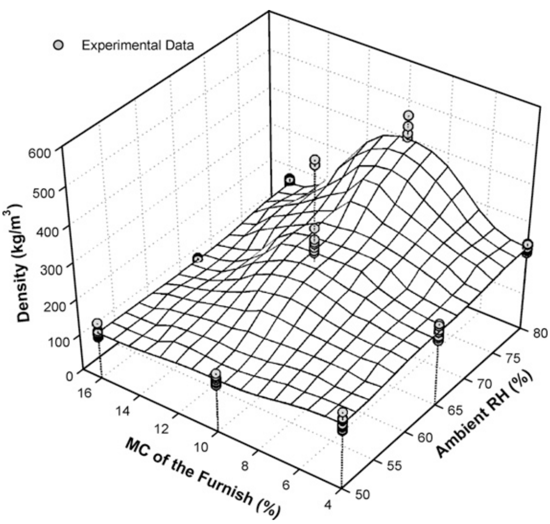

Figure 3. Effects of furnish moisture content (MC) and ambient RH on density.

distance method (SPSS 1996). However, the furnish moisture content had opposite effects. Conversely, regression analysis revealed that at 10% MC of the strands, the effect of RH was more pronounced and the spread of data significantly increased in the more humid environments. In dry (≤50% RH) ambient conditions, the increase of veneer moisture content caused a slight decrease in density. This may be explained by the unknown response of foaming of the matrix (PUR). Because the moisture triggered the cure of the PUR foam, it does appear that the moisture content of substrate was less deterministic compared with the ambient RH. The somewhat erratic behavior of density formulation with strands that have 10% MC at 65 and 80% RH needs further investigation. More in-depth analysis of moisture and foaming of PUR relations was beyond the scope of this project.

Phase II: Compression Strength as a Function of Technological Parameters

Table 3 summarizes the compression strength properties of veneer–PUR core panels by factor–level combinations. Both specimen types with parallel and perpendicular strand alignment demonstrated significantly higher strength values than the pure PUR foam (Table 1). This confirms that veneer strand reinforcements contributed significantly to the compression strength increase of porous foam materials. Large variations, experienced in several experimental runs, are attributable to the presence of noise factors such as alignment imperfections, uneven distribution of resin or strands, etc. However, the factor effect is reflected in the relevant differences between the runs.

The formulated regression models, Eqs 1 and 2, for parallel and perpendicular testing, respectively, indicate significant factorial and interaction effects for the examined parameters.

$$\hat{Y}\sigma_{C_{par}} = 1112.3 - 176.2A + 296.8B - 261.6C + 154.9AB - 157.4BC \quad R^2 = 0.58 \quad (1)$$

$$\hat{Y}\sigma_{C_{perp}} = 261.6 - 80.1A + 90.9B - 76.6C + 22.8AC - 36.3BC \quad R^2 = 0.82 \quad (2)$$

According to Eq 1, the resin content had less impact on compression strength underlining the matrix supporting role of the foam, whereas in the case of perpendicular alignment, all factors have almost the same effect on compressibility. The interaction terms AC (1) and AB (2) of the previous regression models have been pooled in the standard error because of their nonsignificant effect on the means. With the factors set

Table 3. Summary statistics of experimental test results by factor–level combinations.

Run #	Factors and levels: A	B	C	n[a]	Density: $\bar{y}$ (kg/m^{-3})	COV[b] (%)	Compression strength, □ alignment: $\bar{y}$ (kPa)	COV* (%)	Compression strength, ⊥ alignment: $\bar{y}$ (kPa)	COV* (%)
1	−1	−1	−1	6	197	3.8	1388	20	346	8
2	−1	−1	+1	5	174	3.1	983	23	207	10
3	−1	+1	−1	6	253	2.4	1836	25	574	7
4	−1	+1	+1	6	256	2.5	1103	23	288	6
5	+1	−1	−1	6	101	3.2	499	7	115	18
6	+1	−1	+1	6	115	2	587	17	95	12
7	+1	+1	−1	5	207	3.4	1898	37	395	7
8	+1	+1	+1	6	219	4.2	955	21	184	18
9	0	0	0	6	168	4.7	909	28	167	20
10	0	0	0	6	162	3.5	825	37	170	7
11	0	0	0	6	194	2.3	1349	9	291	22
Overall average values					**183**	—	**1121**	—	**257**	—

[a] n, sample size.
[b] COV, coefficient of variation.

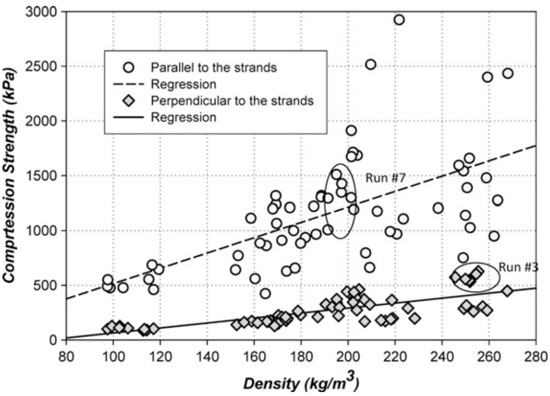

Figure 4. Relationships between density and compression strength in the two loading directions.

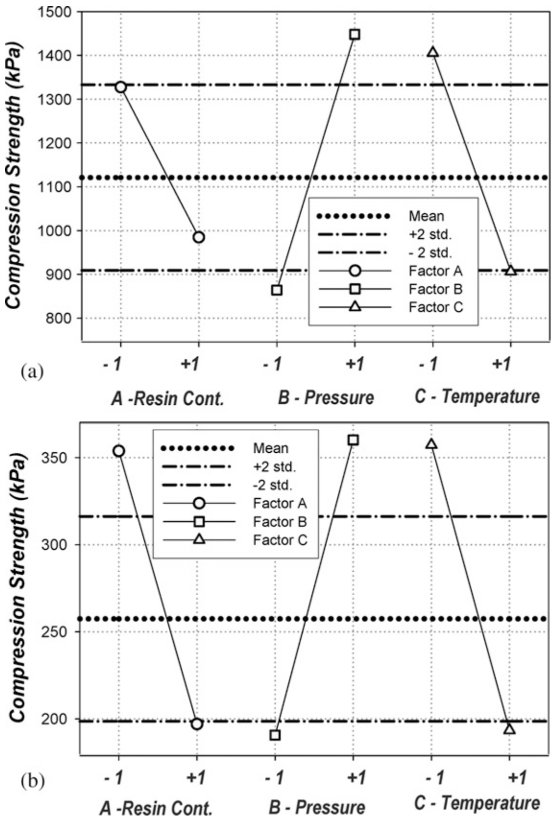

Figure 5. Effects of technological factors on compression strength. (a) Parallel strand alignment and (b) perpendicular strand alignment relative to the direction of applied load.

on an optimal level, an increase of 66% of the mean was detected in the case of parallel alignment. For perpendicular alignment, this increase was almost 90%.

Figure 4 represents the relationship between panel density and compression strengths for both strand orientations. Specimens demonstrated a linear correlation with barely acceptable coefficient of determination when the strands were aligned perpendicular to the loading direction. However, specimens with parallel strand alignment just slightly correlated with the density, especially in the upper region. High and irregular deviations can be attributed to the noise factors previously mentioned. From Fig 4, one can distinguish the individual runs (marked with circles) that indicate that the selected factors have an influence on both density and compression properties. These so-called group effects may be better studied with additional experimental runs with larger numbers of replications.

The marginal effects of the factors (Fig 5) means that any factor had a significant influence on the examined properties if its level setting caused ± 2 SD or higher changes in the property in question relative to its overall mean value. It does appear that the matrix (resin) content in the selected range played an insignificant role when the panels were compressed parallel to strand alignment. The consolidation pressure had a positive linear effect, and temperature bore a negative one. Figure 5a also reveals that the highest compression strength values were obtained when pressure was set to the upper level (55.2 kPa) and temperature had the lower level (25°C). These corresponded to the experimental runs of 3 and 7.

Perpendicular to strand alignment (Fig 5b), all factors had significant effects with similar trends on compression strength. The higher PUR content manifested in lower compression resistance, as expected. This is reasonable, because the buckling of strands with perpendicular alignment was more prominent and the volumetric increase of compressible matrix had a less supporting effect. The low compression strength values discourage the use of this configuration if the product may be exposed to intensive compression forces perpendicular to the plane of the panel.

SUMMARY AND CONCLUSIONS

During this long-term research and development, several compounds and chemical materials were tried in combination with veneer strands. PUR proved to be the most successful matrix. Features influenced the selection, including the quality adhesion to wood without modification of the furnish and lightweight, rapid curing induced by moisture and easy manipulation, ie machining, regluing, and surface covering.

This study reviewed the core formation using statistical process control methods. The discussion included the effects of technological parameters on physical and mechanical properties (ie density and compression strength). The conclusions of this investigation may be summarized as follows.

Generally, PUR is an ideal matrix material for reinforcement with veneer strands because of good physical and adhesion characteristics. However, the orientation of strands, regarding the direction of applied load, has a substantial effect on compression properties. On average, strength when the applied load was perpendicular to the strands was just about 23% of the compression strength measured parallel with strand alignment.

With fixed manufacturing factors, the increasing ambient RH was linearly and directly proportional to the density. However, at 10% veneer strand moisture content and greater than 65% ambient RH, density increased rapidly with substantial spread of data. The moisture content of the furnish was just slightly and inversely proportional to the density.

Overall, the correlation between density and compression strength was weak compared with that for solid wood. Nonetheless, data demonstrated some group effects. Thus, with appropriate selections of technological and environmental parameters, optimization of product performance may be achieved.

Finally, consistent and slightly higher densities could be achieved in dry environmental conditions if moisture content of the wood constituent is decreasing. Typically, increasing ambient RH results in a density increase.

Based on the combination of results obtained by the two segments of this research, it might be stated that in controlled plant environments, with careful selection of other technological parameters, the optimal compression performance can be achieved. Uses for this newly developed composite may include carrier substrates for countertops, interior door leaves, heat and acoustic insulation panels as well as structural insulated panels.

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