A Formaldehyde-Free, Sustainable Alternative for the Engineered Wood Industry

By Dr. Gregory J. Tudryn

Ecovative is a recipient of RadTech's 2014 Emerging Technology Award.

Engineered woods, such as particle board and medium density fiberboard (MDF), are common within the furniture industry as each provides an inexpensive alternative to solid wood construction. Although the physical performance of particle board and MDF is adequate for furniture applications, there are significant legislative drivers for safer structural core materials to limit the emission of volatile organic compounds. The most common resins are urea formaldehyde (UF) or methylene diphenyl diisocyanate (MDI), typically constituting between 7% and 10% of the final product's total mass, which emit toxic volatiles either during or post production.

These resins instituted in the production of traditional engineered wood products (UF, MDI) have recently come under substantial scrutiny due to rising costs (now accounting for upward of 30% of the product cost) and detrimental human health effects. State regulations on the emission of formaldehyde from composite wood products (such particle board, MDF and hardwood plywood) and federal amendments to the Toxic Substances Control Act set formaldehyde emission limits for composite wood products sold in the United States. The National Toxicology Program most recently added formaldehyde, a precursor to engineered woods, to the federal list of carcinogens.

Ecovative has begun to develop a drop-in replacement for engineered wood products (Myco Board™) which is economically competitive and intrinsically safe. This mycological biocomposite is comprised of biobased

FIGURE 1

Mycelium, agricultural waste and grown biomaterial

(Left) 140x magnification of mycelium; (Middle) agricultural waste from the cotton industry; (Right) grown biomaterial that serves as protective packaging, the mycelium is white.

TABLE 1

Physical performance metrics for flat engineered wood products at 0.50” thickness

Metric	Myco Board™	Myco Board™ Laminate	MDF
Density (lbs/ft³)	30	37	53
Modulus of Rupture (psi)	820	1,700	1,595
Modulus of Elasticity (psi)	120,400	336,100	217,500
Screw Hold Strength (lbf)	110	110	132
Internal Bond Strength (lbf)	55	55	44
Energy to Produce (MJ/ft³)	79.5	98.1	234.9
Formaldehyde Emission (ppm)	<0.001	<0.001	5

materials (ASTM D6866), which is unachievable with conventional engineered wood products that rely on synthetic resins. This product is literally grown, and is composed of regionally sourced agricultural waste that is bound with mycelium.

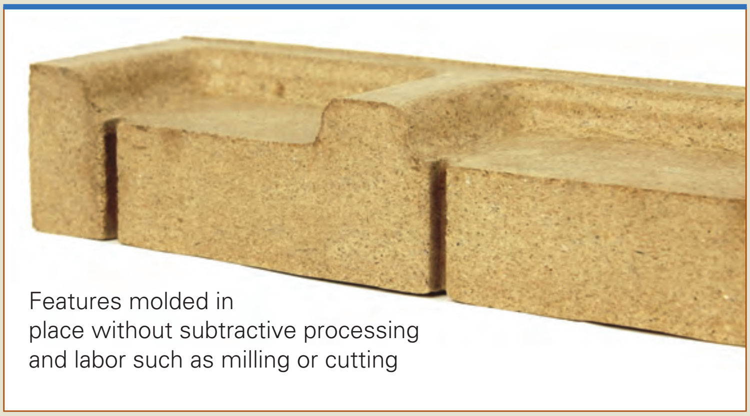
The uniting of this biological composite with UV-curable natural resins enables this biotechnology as a finished boardstock, molded stock and paneling for a broad range of demanding engineered wood markets with both structural and non-structural product offerings. UV curing of natural resins on mycological biocomposites enables the tailoring of surface features such as gloss, texture, coloration and embedding of antimicrobial agents while adding to overall mechanical performance, all with minimal additive and process time. This value-add is important to markets such as engineered woods, and is also applicable to coatings in Ecovative’s core technology of protective packaging using a sustainable, rapid, cost-effective UV process.

This investigation highlights the use of two biologically inspired resins—a self-propagating core bioresin in replacement of formaldehyde, and a naturally derived UV-crosslinked surface coating. The core material is grown using biological resins, and is comprised of lignocellulosic agricultural byproducts bound cohesively into designed shapes by filamentous fungal tissue (mycelium), analogous to traditional composite fillers and resins, respectively (Figure 1). The UV surface coating, developed by Dr. James Crivello (Rensselaer Polytechnic Institute), is comprised of epoxidized vegetable oils and onium salt photoinitiators.

The core material (mycological biocomposite) challenges the current paradigm of synthetic materials and resins. Rather than using high-embodied energy processes and finite resources to manufacture materials, this material takes advantage of regionally sourced agricultural waste to grow the biological resin, which binds the desired product in a self-assembling process. Fungal vegetative tissue (mycelium) propagates and binds to the agricultural fillers as it grows apically into an interconnected fibrous network, analogous to addition-reaction synthetic resins forming *in situ* within a composite material. The mycelium derives its network strength from chitinous cell walls, imparting high flame retardance and elastic modulus, and low thermal conductivity to the composite through

FIGURE 2

Molded mycological composite engineered wood material



Features molded in
place without subtractive processing
and labor such as milling or cutting

FIGURE 3

Mechanical testing fixtures

Mechanical testing fixtures used for testing mycological composites to provide (a) modulus of elasticity, modulus of rupture, and (b) screw withdraw strength following ASTM D1037.

this high-T_g biopolymer. The ability to auto-generate tissue passively throughout the composite offers a substantial reduction in resin cost and processing energy—while remaining renewable, as well as cost- and performance-competitive (Table 1). Additionally, this self-assembling process offers the ability to grow precision features into the final product without further subtractive downstream processing or wasted material (Figure 2).

Materials Preparation

Corn stover agricultural waste is industrially sourced, profiled for nutrition and sorted using market grade mesh sizing (fine to coarse). Sorted materials are grown separately, intermixed or layered to observe the effect of particle size on material packing and surface features. All material is autoclaved prior to inoculation (120°C, 15 psi, one hour), and incubated passively in warehouse conditions to achieve internal resin content in excess of 10% [m:m], which is comparable to the current state-of-the-art. Post processing of core board material is denoted by drying method (convective or conductive). Thermally activated surface coatings are prepared from epoxidized linseed oil, applied manually ($\leq$8g/ft^2) and cured at a temperature of 180°F for a duration of 10 minutes. UV-activated surface coatings are prepared from epoxidized linseed oil and applied manually ($\leq$8g/ft^2), using a 2 x 30 watt UV-C lamp (λ=254 nm) to cure at room temperature at a target distance of 48 inches for a duration of 10 minutes to ensure completion.

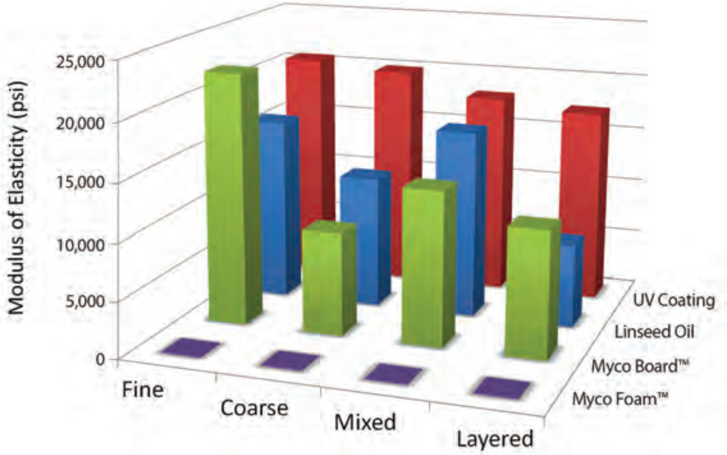
Mechanical Testing

Testing was performed in replicates of 12 on Instron testing machines 3345 and 4411, using ASTM D1037 for Elastic modulus, modulus of rupture and screw withdraw strength, ASTM C303 (EIN323) for density and externally for formaldehyde content using ASTM E1333 (EIN 120) (Figure 3).

Alongside the sustainable and clean solution to engineered wood arises the desire to have an equally eco-conscious coating. Applications of external

FIGURE 4

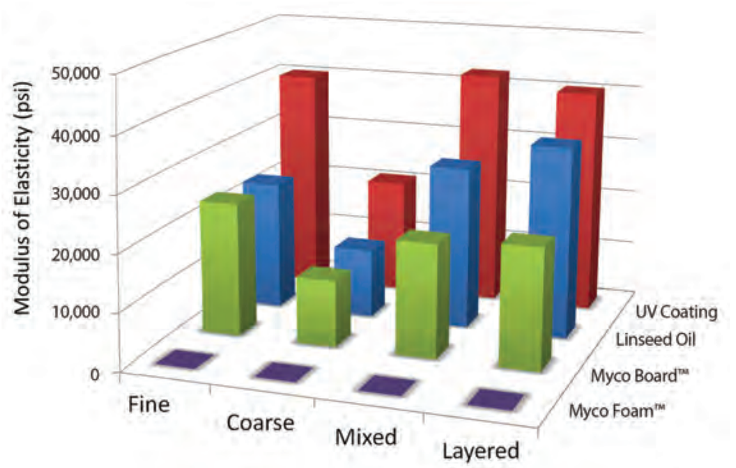
Modulus of elasticity for mycological composites using convective processing



Front axis denotes corn stover filler particle subtype, right axis denotes product treatment (foam referring to low density mycological composite analogs).

FIGURE 5

Modulus of elasticity for mycological composites using conductive processing



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coatings each offer unique drawbacks. Liquid paint requires extensive preparation and often has relatively a high installation cost and low drying throughput. Laminate materials have the ability to be grown into the core material without additional resin; however, the necessity for edge banding or T-molding remains.

Vinyl wrapping offers better conformance than laminate; however, drawbacks include a significant amount of waste foil material and often poorer visual aesthetics. Universally, traditional synthetic coatings often reinstate the selected drawbacks of petroleum-derived resins mentioned earlier. Naturally derived resins historically encounter a slow curing process (e.g., autooxidation of diene bonds), thus limiting throughput. However, photoinitiators (such as onium salts developed by Dr. Crivello's team at RPI) enable the consideration of sustainable epoxy monomer sources, including epoxidized vegetable oil triglycerides such as linseed, soybean, pinene, limonene and others. New photoinitiators demonstrate rapid curing of readily prepared unsaturated oils or commercially available epoxidized vegetable oils, facilitating a rapid processing route that remains sustainable and cost-effective, as well as impart desirable surface coverage and finish characteristics.

Results and Conclusions

Figures 4 and 5 show the modulus of elasticity of mycological composites determined from ASTM D1037, with variation in filler particle size—fine, coarse, mixed and layered (fine particles on the exterior)—in addition to coating type. Figure 4 provides results from the convective drying process of mycological composites. Figure 5 summarizes results from the conductive drying process. The added mechanical strength of thermally cured linseed oil and UV-cured linseed oil is more pronounced in samples subjected to the conductive drying processing. This is due to resultant consistent surface coating properties. At relatively higher contact temperature, conductively dried samples have efficient heat transfer to the mycelium resin, promoting a uniform distribution of fused structural β-glucans (predominantly bound to the structural chitin layer of the mycelial cell wall). This resin sets on the product surface, preventing excess penetration of linseed oil, thus improving the UV exposure during the crosslinking of triglycerides by minimizing inaccessible reactive sites beneath the surface, and as such is reflected in the higher relative mechanical performance.

Mycological composites prepared using fine particles offer good overall space filling and packing, resulting in the highest density (43.6lb/ft^3) and well-resolved features. However, these composites are susceptible to fracture due to a relatively low aspect ratio of fine particles. Coarse particles provide less packing ability under the same conditions as fine particles, but provide more desirable flexural performance due to higher aspect ratios of lignocellulosic filler reinforcement at lower density (21.9lb/ft^3). The open-cell structure of uniform coarse particle results in a rougher surface and higher compressibility than the densely packed fine particles. Mixed particle composites (33.3lb/ft^3) offer higher elastic modulus relative to coarse materials due to the interstitial site-occupying nature of fine particles in a blend. This holds true in either drying process method. This composite blend provides uniform distribution of applied stress, and a facile path for the mycelium to use turgor pressure and, subsequently, propagate and respire as a uniform bioresin.

Finally, layered materials (38.6lb/ft^3) perform similarly to coarse materials when untreated; however, with an applied linseed coating, they display a marked increase in modulus if

FIGURE 6

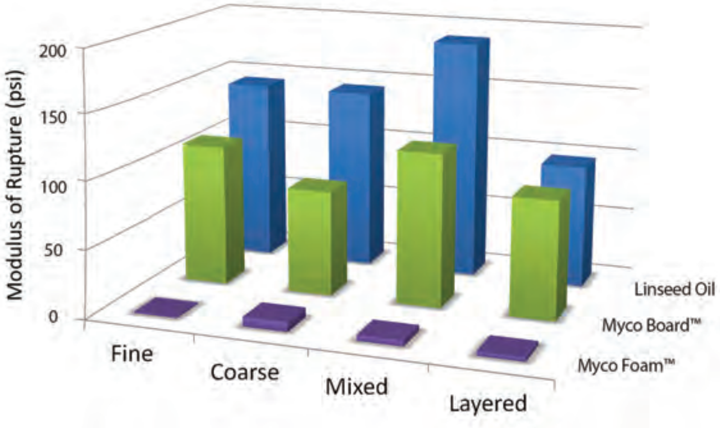
Mycological biocomposite material grown with surface features and a rounded-edge feature, using lignocellulosic waste, convection dried and coated with UV-crosslinked vegetable oil

processed with conductive methods. In all scenarios, the linseed coating and UV coating are more amenable toward conductively processed samples, and the UV coating yields the most desirable finish (Figure 6) and strength (Figure 7). Overall, the mixed particle size composite using conduction processing with UV coating offers the highest performance among the sample sets—with the highest modulus in this study relative to density, and the most aesthetic and uniform surface coating among test samples.

Figure 7 displays modulus of rupture for corn stover mycological composites using conductive drying. The overall values represented here are lower than the products presented in Table 1 due to lack of fibrous lignocellulosic core filler in corn stover; however, stover was selected for the specific nutrition profile for the mycelium selected in this study. Flexural strength (noted in Figure 7) is imparted solely by the biological resin and treatment coating, and can be bolstered using high aspect ratio fibers or veneers (Table 1, Figure 8). These experimental sets are beyond the scope of this investigation. It is observed that the thermally cured coat of linseed oil provides an increase in modulus of rupture, relative to non-coated samples. UV-cured coatings do not impart an additional increase in modulus of rupture on these corn particle subtypes.

FIGURE 7

Modulus of rupture (flexural strength) of mycological composites using conductive processing



Front axis denotes corn stover filler particle subtype, right axis denotes product treatment (foam referring to low density mycological composite analogs).

Summary

A series of mycological biocomposites were grown, processed, surface coated and tested for mechanical performance. The marriage of two bioderived technologies confirm that fungal mycelium composites using agricultural waste are enhanced when used in conjunction with UV-cured epoxidized vegetable oil coatings. The resultant material demonstrates conductive drying of mycological composites is desirable to optimize coating retention at the surface, maximizing UV exposure to minimize processing time. The use of conductive drying bolsters modulus of elasticity and modulus of rupture, while decreasing overall processing time due to efficient heat transfer and further enhances surface coating uniformity. Mixed filler particle sizes provide an optimal environment for biological resin, which is four-fold:

- Improves incubation environment for biological resin formation
- Provides a flat surface for coating application
- Improves stress distribution through desired particle-particle interactions

FIGURE 8

Mycological biocomposite with veneer laminate bound to the agricultural waste and mycological composite core

- Maintains relatively low density with respect to mechanical strength

The verification of a rapidly cured renewable surface coating on mycological biocomposites solidifies a cost-effective, environmentally safe alternative to engineered wood materials. Upcycling agricultural waste using fungal tissue offers green composites competitive in both performance and cost to traditional MDF (Table 1). Epoxidized vegetable oils provide the surface finish aesthetics that can be specifically tuned to incorporate faster cure time, coloration, texture, gloss or antimicrobial activity. These prospects, in combination with high fiber composites or veneers (Table 1, Figure 8), facilitate safe and sustainable options for the non-load-bearing and possibly structural material markets. This combination of innovative design and processing will enable sustainable engineered materials that are lighter and as strong as selections that we have today. Consequently, transportation cost is lessened, air quality is improved and the complete product life cycle improves both health and global environmental impact. ◗

Acknowledgements

This material is based upon work supported in part by the National Science Foundation SBIR under Phase II Grant No. IIP-1152476. The author thanks Todd Aldrich for support in biological preparation and processing, and Dr. James V. Crivello for helpful discussions and coating formulations.

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