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PROTEIN-BASED BIOMATERIALS FOR TEMPORARY CONSTRUCTION

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Abstract
Interest in reducing the environmental impacts of building materials has prompted the development of biobased construction material alternatives from renewable resources. This study investigated the potential for animal-based protein derivatives to serve as low volatile organic compound (VOC), environmentally friendly adhesives for engineered wood products in temporary construction applications. First, the mechanical properties, namely bond strength, of virgin protein-based adhesives were characterized and compared to four commercially available adhesives. The flexural mechanical properties (e.g., flexural strength, flexural modulus of elasticity) of (a) two-ply glue-laminated composites and (b) laminated wood veneer composites manufactured using protein-based adhesives were characterized and compared to conventional engineered wood products, including oriented strand board (OSB), plywood, particleboard, and medium density fiberboard (MDF). In comparison to conventional adhesives and engineered wood products, the results suggest that protein-based adhesives have the potential to be used in construction as environmentally friendly wood adhesives and that protein-adhered laminated wood composites exhibit a potential to replace traditional engineered wood products, especially in formwork, scaffolding, and other temporary construction applications.

Keywords:
Biopolymer; Protein; Gelatin; Adhesive; Mechanical Properties; Temporary Construction

1 INTRODUCTION

The rising popularity of local, national, and international green building certification programs have accelerated the global demand for construction materials that possess significantly smaller ecological footprints than their conventional counterparts. Increased interest in resource conservation and waste reduction in the construction industry has further fueled the development of biobased, biorenewable, low-toxicity building materials and materials with high recycled or reclaimed constituent contents.

1.1 Engineered wood

From a global perspective, wood and engineered wood, including dimensional lumber, plywood, glue-laminated lumber, and particleboard, are among the most prevalent materials used in construction and building applications. Despite being manufactured in large part from biorenewable resources, engineered wood products are typically fabricated using adhesives that emit volatile organic compounds (VOCs) – noxious compounds that volatilize at room temperature [Djagny 2001]. Much research has correlated VOC exposure with human-health toxicity and elevated risks of cancer, liver damage, kidney failure, and damage to the central nervous system [Jia 2008; Wallace 2001].

Engineered wood products are used extensively in temporary construction applications (e.g., scaffolding, formwork), where conventional, highly recalcitrant and chemically resistant adhesives may not be necessary. For example, the use of high-strength, ultra-water-resistant adhesives to ensure in-service performance in impermanent structures may actually compromise the biodegradability of engineered wood products once they are landfilled.

Recent research has focused on reducing the environmental impact of noxious construction adhesives [Imam 2001]. While the development of starch-based adhesives has received much attention in recent years [Moubarik 2010], starch-based materials require chemical or physical modifications to enhance their adhesive properties. In addition to starch, authors have noted the promising adhesive properties of other natural polysaccharides and proteins, such as soy, sericin, and gelatin [Lei 2014; Zhu 1995; Kim 2013].

1.2 Gelatin

Gelatin is synthesized *via* partial hydrolysis of collagen from the skins, bones, and tendons of animals in alkaline or highly acidic solutions. In 2007, the global production of gelatin was approximately 326,000 tons, of which 46% and 29% was derived from porcine and bovine skin, respectively.

Gelatin-based materials have many advantages, including the potential, like many biopolymers, to be manipulated during processing to tune their material properties. These properties largely depend on the polydispersity and amino acid sequence of the source proteins [Gioffre 2011]. In addition to good mechanical properties, gelatin has other notable advantages, including renewability, biodegradability, global availability, nontoxicity, and low cost.

Despite the positive benefits of gelatin, one prominent disadvantage is gelatin's proclivity to absorb water. While water is well known to influence the physical and mechanical properties, the initial mechanical and adhesive properties of gelatin make it a potential candidate for construction adhesives, especially in temporary building applications where potential water exposure is limited to a timescale of only a few days.

1.3 Research objectives

The objective of this work was to preliminarily assess the potential for virgin protein-based adhesives to satisfy both environmental and structural criteria for wood and engineered wood products for use in temporary construction applications. In this study, protein-based adhesives were synthesized from commercial gelatin sources. The breaking strengths of virgin gelatin-based adhesives were characterized via tensile testing and compared to the breaking strengths of four (4) commercially available adhesives, along with measures of their VOC toxicity. The flexural strength and stiffness of two (2) engineering oak wood-gelatin composites – a two-ply gelatin-oak glue-laminated composite and a five-ply laminated gelatin-oak veneer composite – were also characterized via three-point bending and compared to five (5) engineered wood products, namely plywood, oriented strand board, medium-density fiberboard, and particleboard.

2 MATERIALS AND METHODS

2.1 Materials

Powdered gelatin was commercially obtained from Knox (Kraft Foods, Inc.) in granular form. Oak wood substrates and oak veneers were obtained at a local hardware store. Four adhesives, namely Gorilla Glue, Liquid Nails, Titebond, and Weldbond, were also commercial obtained from a local hardware store.

2.2 Gelatin adhesive and composite preparation

A 100 mL beaker of water was heated to 40°C. Powdered gelatin (40g), was added to the water and allowed to dissolve for 10 minutes under continuously stirring by a magnetic stir bar.

For testing the adhesive strength (breaking strength) of the gelatin, oak wood substrates were cut into strips 100 mm x 20 mm x 7 mm. Four (4) mL of the hot gelatin adhesive sample was placed on a 20 x 20 mm splice area to secure three oak wood strips together. The oak wood strips were glued and allowed to cure for seven days prior to testing. Adhesive test samples using the commercial wood adhesives were fabricated in a similar fashion.

In addition to the adhesive samples, two (2) engineered oak wood-gelatin composite families were manufactured. A two-ply gelatin-oak glue-laminated composite was fabricated by applying a thin layer of gelatin adhesive between two oak strips 250 mm x 20 mm x 7 mm. A five-ply oak wood veneer composite was fabricated by gluing five plies of 130 mm x 20 mm x 0.7 mm oak veneers in a similar fashion. The samples were fabricated and allowed to cure for seven days prior to mechanical testing at ambient conditions.

The three sample geometries are shown in Fig. 1.

2.3 Mechanical testing

The breaking strengths of the adhesive-bonded wood samples were characterized according to a modified ASTM D1002 standard tensile test method. The test was conducted using an Instron 5869 Universal Testing Machine and a displacement-controlled rate of 0.83 mm/s. Five (5) specimens of each of the gelatin and commercial adhesives were tested (Fig. 1a.).

The flexural mechanical properties, namely flexural strength and flexural stiffness, of the engineered 2-ply laminate and 5-ply veneer composites were characterized in three-point bending according to ASTM D790 using an Instron 5869 Universal Testing Machine and crosshead rates of 0.1 mm/s and 0.025 mm/s, respectively. Five (5) specimens of each composite laminate (Fig. 1b. and 1c.) were tested.

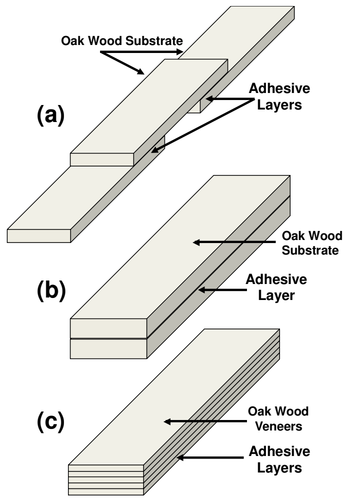

Fig. 1: Gelatin composite sample geometries, including (a) gelatin adhesive tensile specimen, (b) two-ply gelatin-wood composite flexural specimen, (c) five-ply gelatin-wood composite flexural specimen.

3 RESULTS

3.1 Adhesive breaking strength

Figure 2 shows the breaking strength of the gelatin-based adhesives (G) in comparison to four commercial adhesives: Gorilla Glue (GG), Liquid Nails (LN), Titebond (T), and Weldbond (W). The data suggest that the strength of the gelatin-based wood adhesive is comparable to, or greater than, commercially available adhesives. For example, the breaking strengths of the LN and GG adhesives were 82% and 87% less, respectively, than the G samples. The breaking strength of the G adhesives was also comparable to the strengths of the T and W samples. The breaking strength of G only varied -4.1% and +1.5% from the T and W adhesives, respectively.

The data also suggest that the gelatin-based adhesives are much lower in VOC content than any of the commercial adhesives investigated herein. While the gelatin-based adhesives contain 0 g/L of VOCs, manufacturer reported data for the GG and LN samples contain 12 g/L [The Gorilla Glue Company 2013] and 46 g/L [Asks Nobel Paints LLC], and the T and W contain 5.6 g/L [Franklin International 2014] and 9.0 g/L [Frank T. Ross and Sons Ltd. 2013] of VOCs, respectively. Together, these data demonstrate that the gelatin-based adhesives are both mechanically and environmentally competitive with the commercial adhesives investigated herein.

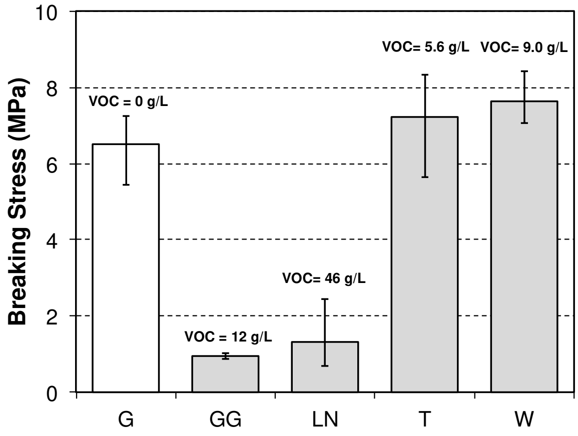

Fig. 2: Breaking strength and VOC content of gelatin-based adhesives compared to commercial adhesives.

3.2 Flexural mechanical properties

The load-displacement behaviors for the five (5) two-ply gelatin-wood composite samples (see Fig. 1b). are shown in Fig. 3. The characteristic responses of four samples (shown in grey) exhibit an average peak load of approximately 1522 N, while one sample incurred delamination of the adhesive layer during testing (shown in black).

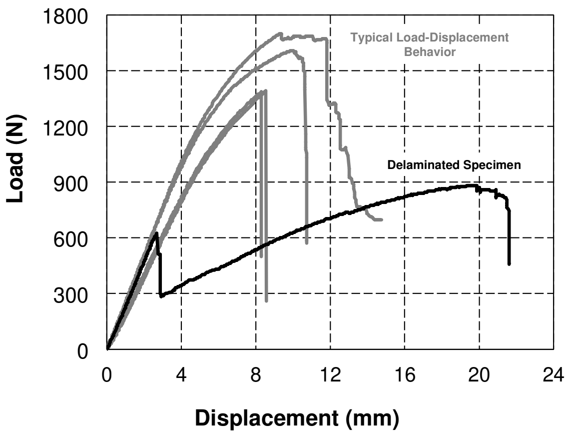

Fig. 3: Load displacement behavior of two-ply gelatin-wood composite specimens.

The non-delaminated samples show consistent results in regard to the load-displacement behavior. These samples ultimately failed in tension of the oak wood at the extreme tensile fibers (bottom surface). This result proves that the shear strength of the gelatin was sufficient to withstand the maximum shear stress that develops at the midline of the cross-section in three-point bending. As expected of laminated materials that lose composite action, the delaminated sample achieved an ultimate peak load of 886 N, approximately half of the total peak load of the laminated, adhered specimens.

The moduli of rupture (flexural strengths) of the two-ply (see Fig. 1b.) and five-ply (see Fig. 1c.) are shown in Fig. 4a, along with the flexural strengths of four common engineered wood products, namely OSB, MDF, plywood, and particleboard. As can be seen in the figure, both the two-ply and five-ply composites exhibit superior and comparable strengths over the conventional engineered woods, respectively. The strength achieved by the two-ply composite is due, in large part, to the size and geometries of the pristine oak substrates used in the manufacture of the specimens. Contrastingly, the five-ply composite specimens were manufactured with oak veneers. These smaller layers inherently exhibit more variability in material properties than the bulk oak substrates used in the two-ply samples. It follows that the two-ply composite achieved a 226% increase in flexural strength over the two-ply composites. Both the two- and five-ply composites, however, exhibited flexural strength increases of 266% and 12% over conventional plywood, respectively.

The moduli of elasticity (flexural stiffness) of the two-ply (see Fig. 1b.) and five-ply (see Fig. 1c.) are shown in Fig. 4b, along with the flexural moduli of the four traditional engineered wood products. As can be seen in the figure, the two-ply composite again exhibits superior average stiffness over the conventional engineered woods. The average stiffness of the five-ply composites, however, was significantly lower than the other engineered wood products. For example, the five-ply composites exhibited a stiffness of 73% less than its most similar counterpart, plywood.

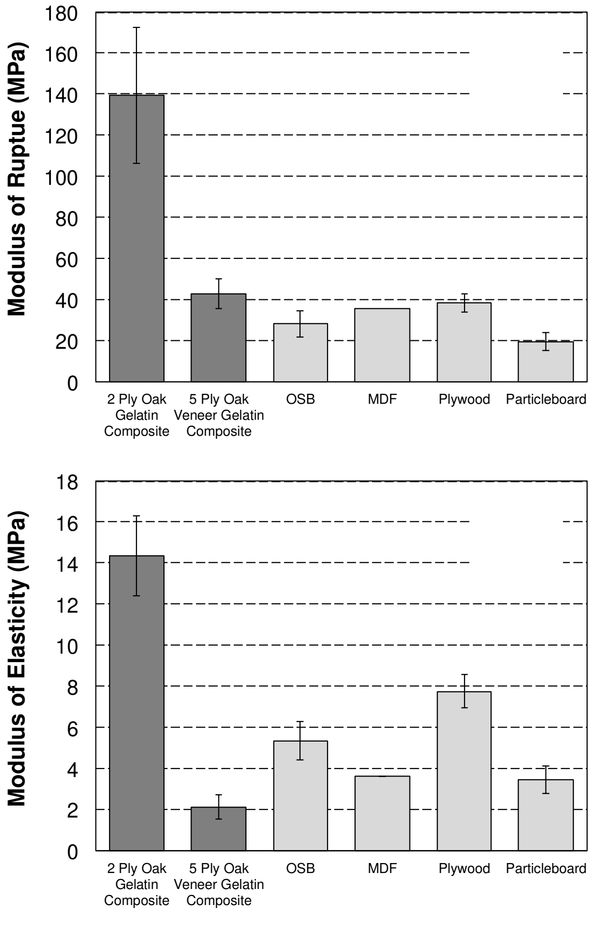

Fig. 4: Comparison of (a) flexural modulus of rupture and (b) flexural modulus of elasticity of gelatin-wood composites and engineered wood products.

4 DISCUSSION AND FUTURE WORK

The mechanical property and toxicity (VOC) data presented herein suggest that biodegradable gelatin-based materials demonstrate good potential to become a viable, low-VOC alternative to commercial wood adhesives. The breaking strengths of the gelatin adhesives, which emit no VOCs, were comparable or stronger than leading commercial adhesives that contain high levels of VOCs, which are known to cause adverse human-health effects. Due to its manipulability and ability to bond well with wood and natural fibers, virgin gelatin has the potential to serve in a wide variety of adhesive applications in the packaging, automotive, and construction industries – particularly in temporary applications if long-term moisture issues are of noted concern. In addition, the thermal properties of cured, dehydrated gelatin films have been shown to be sufficient for applications in construction. Fakirov (2007) reported that the glass transition of gelatin is on the order of 217°C -- a threshold that far exceeds any thermal demands in construction applications.

4.1 Limitations due to moisture absorption

As discussed, one significant challenge for gelatin-based materials is its hydrophilicity. Due to its chemistry, gelatin absorbs moisture when exposed to water or water vapor. Given that moisture exposure is inevitable in building and construction applications, this quality of gelatin and similar proteins may limit their application to non-permanent building materials and products (e.g., formwork, scaffolding, temporary housing) or non-structural building materials that are not exposed to moisture (e.g., furniture, finishes).

It is well known that the water resistance of gelatins can be improved via chemical functionalization with hydrophobic additives (e.g., tannin, starch, chitosan, oligosaccharides) [Peña 2010], and these methods are currently being explored in more detail.

4.2 The sustainable materials dilemma

As discussed, improving the moisture resistance in gelatin-based building materials may actual compromise the ability of the materials to readily degrade. This represents a fundamental dilemma faced by sustainable building materials. When materials are engineered to be both sustainable and resilient, a balance must be struck between the anticipated serve life and durability of the material and its end-of-life disposal and biodegradation.

While low moisture resistance and biodegradability of gelatin may be seen as a challenge in terms of long-term durability, it may also be an advantage for future green building projects that incorporate strategies for planned obsolescence -- strategies that advocate for materials that are designed to degrade in service (e.g., roofing, siding, temporary support structures). The advantages of designing materials to readily degrade in-service include reductions in material waste and energy for transport, sorting, recycling, and reuse.

To quantify and evaluate the environmental advantages of protein-based materials, investigations on the environmental impacts of these materials must accompany materials development and testing. Current research is underway to substantiate the environmental benefits of protein-based biomaterials in comparison to conventional wood and engineered-wood construction materials via lifecycle assessment methodologies.

4.3 Limitations due to protein source

Another challenge for protein-based materials is the variability in achievable material properties, which can differ significantly depending on the protein source. Gelatin, for example, is well known to exhibit varying properties depending upon the source (e.g., porcine, bovine, fish) and processing method [Gómez-Guillén 2002]. These differences, which can be attributed to differences in amino acid contents and their behavior at low and high pH, represents a grand opportunity to leverage the tunability of the mechanical and thermal properties of protein-based materials by blending proteins from various sources.

5 SUMMARY

This study evaluated the environmental and mechanical potential for a biorenewable protein source, namely gelatin, to serve as an environmentally friendly construction adhesive for wood and engineered wood products. The adhesive strength (breaking strength) was characterized via tensile testing and the flexural mechanical properties of (a) two-ply gelatin-wood glue-laminated composites and (b) five-ply gelatin-wood laminated veneer composites were characterized using three-point bending. The results were compared to commercially available adhesives and engineered wood products currently used in construction applications.

The following represent the main findings of this work:

1. Using metrics of (i) adhesive properties and (ii) environmental impact (low-toxicity), gelatin-based adhesives were favored in comparison to the four commercial adhesives (Gorilla Glue, Liquid Nails, Titebond, Weldbond) investigated herein.
2. Two-ply composite laminates exhibited superior mechanical flexural strength and stiffness compared to engineered wood products, namely plywood, medium-density fiberboard (MDF), oriented strand board (OSB), and particleboard.
3. Five-ply specimens, while less stiff than plywood, MDF, OSB, and particleboard, also demonstrated an increase in flexural strength over conventional engineered wood products.

The variability and tunability of protein-based materials represent a significant opportunity for the tailored design of next-generation construction materials. The fundamental chemistries of proteins, which are highly dependent upon protein source and amino acid sequence, have the potential to be functionalized for desired material properties (e.g., strength, moisture resistance) for permanent and non-permanent construction applications.

6 ACKNOWLEDGMENTS

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