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Procedia Materials Science 6 (2014) 2 – 9

Procedia Materials Science

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3rd International Conference on Materials Processing and Characterisation (ICMPC 2014)

Comparative Study of Bond Strength of Formaldehyde and Soya based Adhesive in Wood Fibre Plywood

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Abstract

Plywoods, particleboards and medium density fibreboards are currently used in the construction of houses, furniture, partitions, etc. These usually incorporate some form of formaldehyde as part of the adhesive system. Formaldehyde-based adhesives are known to be harmful as formaldehyde emissions during manufacture and after installation are known to be carcinogenic and have other undesirable health effects. This and other environmental concerns have in the recent past led to an interest in 'green' adhesives from biological sources that are sustainable and environmentally friendly. Green adhesives are one of the green building practices, which aim to construct buildings that are environmentally responsible, economically viable and healthy places to live and work. The objective of this investigation was to explore environmentally friendly biobased adhesives for plywood manufacturing. This study proposes a natural biobased adhesive that was developed using soya flour, phenol, Plaster of Paris and an agro-based powder as the binder. A comparison of modulus of rupture of the plywood developed using the proposed soya-based adhesive with popular plywoods, including the traditional urea-formaldehyde based plywood has also been undertaken. The three-point bend test (to identify the modulus of rupture) was conducted for all the plywoods compressed at a fixed pressure. It was observed that the soya-based adhesive imparts greater strength to the plywood than the formaldehyde-based adhesive. It is also desirable for wood and wood-based composites to have fire-retarding and microbial-resistant properties by utilising non-toxic additives and treatments. Traditional methods of achieving these objectives have been harmful; for example, timber has been treated with arsenic-based chemicals to make it resistant to microbes. This paper also presents future research directions to render wood-based composites free of toxic additives as well as being sustainable and environmentally friendly.

Keywords: Formaldehyde; Soya based adhesive; Modulus of rupture

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Selection and peer review under responsibility of the Gokaraju Rangaraju Institute of Engineering and Technology (GRIET)
doi:10.1016/j.mspro.2014.07.002

1. Introduction

In recent times there has been an increasing demand for developing composite substances using natural and biobased components which may be used for building and construction purposes like flooring materials, partition boards, plywood and pre-framed roofing with low cost and high durability. Biobased materials are those that primarily use biological and renewable agricultural resources. PVC (polyvinyl chloride) and paper flooring with soyabean oil were the most common housing material in the past in countries like Korea (Kim, 2009). These materials were later on replaced by wood. Since solid wood is quite expensive, plywood and fibreboards are preferred. Nowadays, medium density fibreboards (MDFs) have several potential applications in many fields and their rate of manufacturing is increasing across the world. Cabinet doors, shelves, laminated floors, furniture, panels for building construction are typical products of MDFs. The commonly used method for producing MDFs employs wood-based raw materials. The majority of wood raw materials are mainly utilized for timber products and in the pulp and paper industry. Because of this and also because of environmental and economic considerations, demand for non-wood lignocellulosic fibre resources is also increasing. Currently the most commonly used non-wood materials are bamboo, hemp, jute, kenaf and bagasse as well as cereal straws (El-Kassas and Mourad, 2013).

In plywood as well as fibreboards, the most commonly used adhesive material is based on formaldehyde, such as urea-formaldehyde and melamine-formaldehyde (Halvarsson et al., 2008). Such materials that employ some derivative of formaldehyde as adhesive are harmful as the formaldehyde emissions are known to cause irritation of the skin, eyes, nose and affect the upper respiratory system. A high level of exposure is known to even cause some types of cancer. The International Agency for Research on Cancer, a division of the World Health Organization, has reclassified formaldehyde from a group 2A suspected carcinogen to a known carcinogen (International Agency for Research on Cancer, 2004). Hence, environmental regulations will continue to challenge the construction and fibreboard industry as formaldehyde-based adhesives have been used in plywood and MDF because of their low cost and fast curing characteristics.

Due to the known harmful nature of formaldehyde emissions, many studies have been conducted to reduce the level of formaldehyde emissions from wood materials (Kim, 2009; Sung et al., 2013). In the recent past, with the green building practices gaining worldwide popularity, the various green (or biobased) adhesives have been developed (Pizzi, 2006). A green building aims to enhance the well-being of its occupants and minimize the negative impacts on the community and natural environment by taking a holistic approach to design, siting, construction, and operation (Office of Energy and Sustainable Development, 2014).

Various biobased formaldehyde-free adhesives have been developed in the past few years and the interest has been growing. Some examples of biobased adhesives that have been developed are based on condensed tannins (Pichelin et al., 2006), lignin (Ghaffar and Fan, 2014), vegetable oils (Pizzi, 2006) and soy protein and soy flour (Liu and Li, 2007; Mo and Sun, 2013). Although these biobased adhesives have been developed, there are still challenges in finding the proper chemistry to make these adhesives even more competitive when compared with the traditional petroleum-based ones (i.e. formaldehyde-based adhesives).

This study aims to explore soya-based adhesives for plywood manufacturing. A natural biocomposite based adhesive that was developed using soya, phenol, Plaster of Paris and an agro-based material as the binder is proposed in this study. A comparison of the modulus of rupture of the plywood developed using the proposed adhesive with commonly used plywoods, including the traditional urea-formaldehyde adhesive based plywood, has also been undertaken. The three-point bend test was conducted for the plywoods compressed at a fixed pressure and temperature to identify the modulus of rupture. It was promising to observe that the soya-based adhesive imparts greater strength than the formaldehyde-based adhesive. In the following sub-sections, the experimental setup and procedure that was used in this study is first presented. This is followed by the results and discussion based on those results. Since biobased adhesives and other construction material would be extensively used in the future, a brief section on future research directions is then presented. Finally, conclusions drawn from this study are presented.

2. Experimentation

In this experiment, the proposed green alternative to commonly used petroleum-based wood adhesive that uses soya flour as the major component along with other chemicals is presented. Soya flour is obtained from soya seeds. Apart from soya flour, carbolic acid is also used (usually termed as "Pure Phenol" C6H60). It appears to be colorless to light pink and has a very sharp odour during the heating of the biocomposite. Necessary precautions were taken while handling phenol due to its propensity to burn. Phenol has a melting point of 40.5 degrees, making it a solid (crystal) at room temperature. The pre-experimentation procedures included liquefying the phenol crystal by immersing the phenol bottle in a hot water bath. Eucalyptus veneers were cut according to the dimensions 100 mm × 50 mm × 1 mm. These veneers are in general made by sawing, slicing, or shaving wood into very thin sheets. This material was procured from a local plywood manufacturing unit. During the pre-experimentation itself, these veneers were cut along the grains and texture, whereas a few were cut against the grain orientation.

An agro-based adhesive powder which is processed especially for this experiment is termed as "Adhesive-A" in this study. It is odorless and appears to be white in color. What makes Adhesive-A really special is that it serves its purpose on addition of little amounts only. The most crucial aspect is preparing the adhesive. In this study, two different batches of soya adhesives were prepared. The first batch consisted only of a combination of soya flour and phenol. Whereas, in the second batch, 15% Plaster of Paris and Adhesive-A were used as the supporting binder for the soya and phenol mixture. These ingredients and the supporting material used are shown in Fig. 1.

Fig. 1. Ingredients and supporting material used to manufacture the plyboard
(Note: PoP is Plaster of Paris)

In the first batch, the adhesive was prepared by adding 500g of soya flour into a medium sized beaker with blades. The blades are rotated, during which the liquefied phenol is added into the beaker. The resultant mixture is obtained as paste. Without any delay, the paste is applied evenly on the veneer layer which has a horizontal grain texture, which is followed by a veneer layer with vertical grain texture. Such an alternative layer arrangement (of veneer layers with horizontal and vertical grain texture) is done for up to five layers with the soya paste adhesive in between the layers.

In preparing the adhesive for the second batch, unlike in the first batch, Adhesive-A along with Plaster of Paris was first added to the soya flour in the beaker and later phenol was added. The obtained paste is applied in between the veneers in the same manner as done for the first batch. Supporting steel plates are kept at the top and bottom of the five layer veneer bundle and the composite is pressed at a pressure of 150 bar for 9 to 20 minutes. The experimental setup for the preparation of these samples is shown in Fig. 2. After manufacturing of the ply samples, the material is allowed to cool to room temperature. The samples manufactured with urea-formaldehyde, with soya and phenol only (batch 1) and with soya, phenol, Plaster of Paris and Adhesive-A (batch 2) are shown in Fig 3.

The plywood samples thus prepared were cut to required sizes and then tested for their modulus of rupture. Modulus of rupture (also known as flexural strength, bend strength or fracture strength) is a mechanical parameter for brittle materials like plywood, which is defined as the material's ability to resist deformation under load. The modulus of rupture represents the highest stress experienced within the material at its moment of rupture. The modulus of rupture of the plywood made using the soya based adhesive using the experimentation described above is compared with the strength of existing plywood materials available in the industry. These included plywood made from pure teak wood, from sugarcane bagasse, from particulate plywood composite and plywood manufactured using urea-formaldehyde as the adhesive. Since there are fibres in most of these composites and there will be transgranular cleavage fracture in them, very slow crosshead speeds were selected for the test (0.3 mm per min). Data were recorded for every 2 mm of advancement made by the bending tool. Three samples were tested using a similar setup and the average of the data is taken for the analysis.

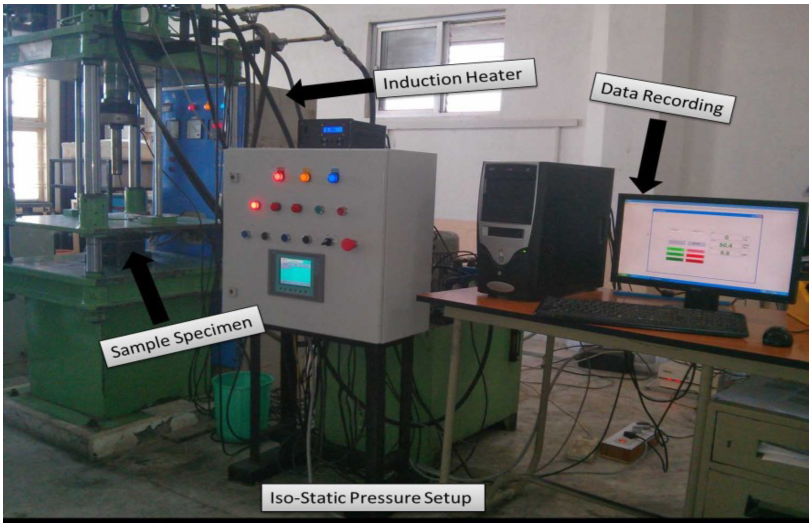

Fig. 2. Experimental setup used to isostatically press the composite at a certain temperature and pressure

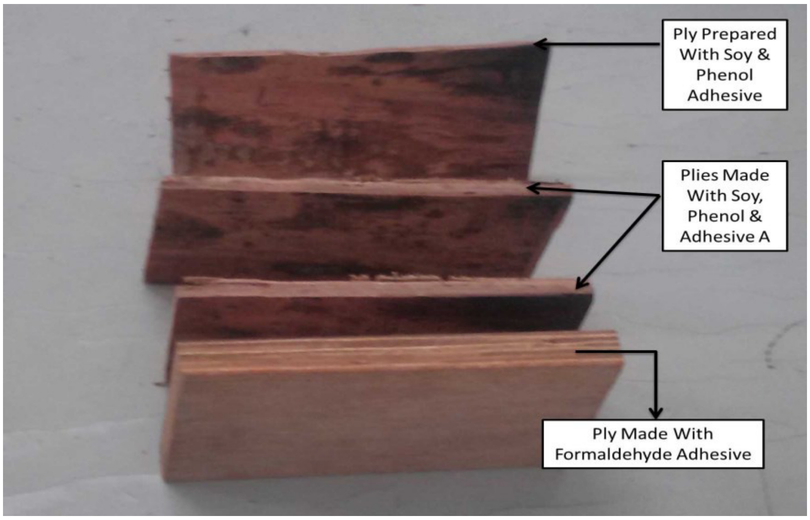

Fig. 3. Plywood manufactured by Soya-Phenol and formaldehyde based adhesive

3. Results and Discussion

The modulus of rupture calculated for the various materials used in the experimentation are presented in Table 1. It should be noted that the plywood prepared in the first batch (i.e., using only soya flour and phenol as the adhesive) did not form well and hence the bend test could not provide accurate modulus of rupture values. Hence the results are presented only for the plywood prepared in batch 2. It is also worth mentioning that in batch 2, when Adhesive-A and Plaster of Paris were added to soya and phenol, the quality of the adhesive had improved to a large extent.

From Table 1, it can be seen that the modulus of rupture for teak wood is highest (i.e. 63.36 MPa) as it is known to be one of the strongest wood, but this wood is rare and expensive. Sugarcane bagasse ply is having modulus of rupture of 18.77 MPa and the raw material is cheap in the regions of the world where sugarcane is grown. But these plywoods are subjected to fungal and other bacterial attacks over a period of time. Particulate material is the wood dust coming out of various processes and its rupture strength is very low, but the raw materials are cheapest. The modulus of rupture of the plywood manufactured by urea-formaldehyde is quite high as compared to the earlier two plywoods. But the plywood manufactured by soya-based adhesive with agents like Phenol and Adhesive-A (prepared in batch 2) is much stronger than even the plywood made from formaldehyde-based adhesive.

Samples were cut from urea-formaldehyde plywood and also from the batch 2 plywood using the soya based adhesive and their micrographs (digital images taken through a microscope) are presented in Fig. 4 and Fig. 5. In case of formaldehyde based adhesive, since it is a less viscous adhesive, voids in the wood near the glued surface were filled with the adhesive (as presented in Fig. 4). On the other hand, in case of the soya-based adhesive, there are some voids near the glued surface. Since Plaster of Paris was mixed with the soya flour, some hard particles are also visible in the adhesive region of the plywood. But the soya-based adhesive produces a stronger bond as it had a higher modulus of rupture. It is expected that the soya-based adhesive would yield a higher strength if the adhesive penetrates deep into the wood fibres (as in the case with the urea-formaldehyde adhesive). Further experiments would be undertaken to make this soya-based adhesive less viscous.

Table 1. Modulus of rupture of various plywoods

Material	Modulus of rupture (MPa)
Teak wood ply	63.36
Sugarcane bagasse ply	18.77
Particulate ply	6.67
Urea-formaldehyde adhesive ply	38.12
Soya-based adhesive ply	45.93

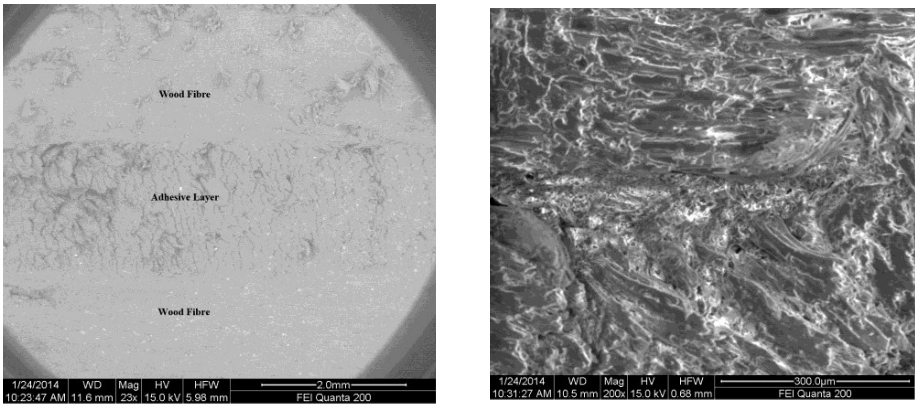

Fig. 4. Micrographs of urea formaldehyde adhesive in the wood fibres

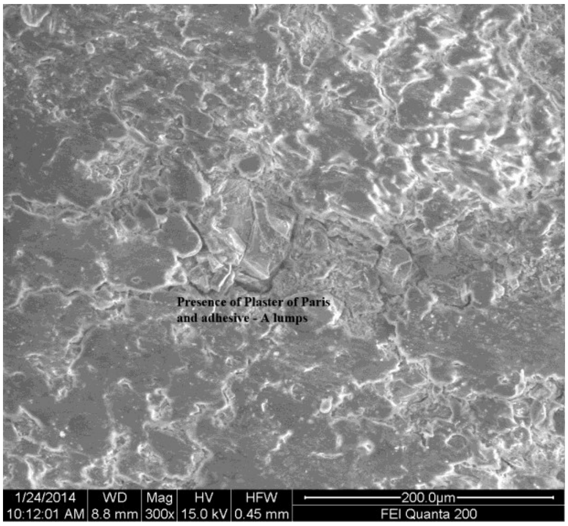

Fig. 5. Micrographs of Soya based adhesive in the wood fibres (from batch 2 ply)

4. Future Research Directions

In the last few decades, concerns related to environmental degradation and human health risks have become the major factors that have propelled research on biobased (or green) building materials and sustainable practices. With the accelerating impacts of global warming and climate change (which are evident worldwide), the demand for biobased materials would only increase in the future. Hence, this section aims to discuss some of the future research directions with regards to developing biobased alternatives to timber in the building and construction industry. The authors acknowledge that this discussion is not exhaustive and is only an attempt to bring out some of the key research issues associated with biobased construction materials.

The aim of the study presented in this paper was to develop a biobased adhesive that would be used as a substitute for toxic formaldehyde. As discussed earlier in this paper, a considerable amount of research has already been undertaken throughout the world on developing biobased adhesives (Pizzi, 2006; Imam et al., 2013). Extensive research has also been undertaken to not just develop biobased adhesives, but also to replace the wood-based fibre with biobased materials. For e.g., rice straw has been used as a raw material in the production of MDFs and high density fibreboards (Halvarsson et al, 2010, Hiziroglu et al, 2008). Rice straw possesses higher wax, ash and silica contents compared to other straws and wood. Chemically, lignocellulosic rice straw fibres have a relatively similar composition to that of other natural fibres (like that of wood, flax, jute, sisal, etc.) that are used in the fibreboard manufacturing industry (Yao et al 2008). The most important benefits of selecting the rice straw (which is an agricultural residue and is grown abundantly in many areas of the world) for MDF production are the reduction of open-field burning of the husk (as it is an agricultural waste), which in turn reduces carbon dioxide emissions. In addition, the rice straw based MDF panels can be recycled or converted to energy after utilization. Sugarcane bagasse, which is also one of the largest agricultural residues in the world, has also been used as a biocomposite material (Loh et al, 2013). Other non-wood biobased materials that have been used include hemp, jute, kenaf and bamboo (El-Kassas and Mourad, 2013). Such biobased materials reduce waste (being bio-degradable) and also ease deforestation by substituting for wood.

Rice straw fibres have a thin wax layer that covers the epidermal cells/outermost surface cells. This wax layer acts as an obstacle to the penetration of the adhesive and for proper gluing of the straw or in other words, it acts as a barrier for the absorbance of water-based adhesives. Removing this wax layer is considered to be a technical and research challenge for the production of rice straw based fibreboards. On the other hand, as discussed earlier, sugarcane bagasse based material are prone to fungal and other bacterial attacks. Thus, numerous research challenges remain in the development of biobased fibreboards.

Future research would also aim to improve 1) microbial-resistant and 2) fire-retarding properties of biobased construction materials by utilising non-toxic additives and treatments. In the past, these properties of wood materials have been improved by using harmful and toxic methods. For example, timber has been treated with arsenic-based chemicals to make it resistant to microbes. Use of such toxic chemicals can have disastrous consequences, a recent example being that of the incidents in the aftermath of hurricane Katrina in 2005. In the flooded city of New Orleans, among numerous potential sources of toxins and environmental contaminants were the metal-contaminated soils that were typical of old urban areas where construction timber was preserved with creosote, pentachlorophenol, and arsenic (Reible et al., 2006). The serious health problems caused to the people exposed to the hazardous chemicals (including emissions from fibreboards) emphatically underscores the need for research and development of biobased construction materials.

Various chemicals have been used to make timber resistant to decay and fungi (Singh et al., 2013, 2014). Future research could look into adding additives to the biobased material during the construction of the fibreboard or the adhesives itself. Novel ideas can be taken from the field of food packaging, where various natural preservation techniques have been employed (Kuorwel et al., 2011).

Fire retarding properties are also an important part of developing any biobased construction materials. This would especially be of significance if the developed construction material would be used in areas prone to bushfires. Because of increasing extreme temperatures and heatwaves due to climate change, many regions of the world would experience increased chances of fire and more bushfires (McEvoy et al., 2012). Thus, knowledge about the high temperature (i.e. fire) performance of the developed biobased materials would also be an important research topic for the future.

5. Conclusions

Moduli of rupture of various biocomposite plywoods were compared in this study. The soya-based adhesive that was developed was found to be having a higher modulus of rupture than the petroleum-based urea-formaldehyde adhesive. In addition to being stronger, plywoods using such biobased adhesives are free of the harmful formaldehyde emissions (a known carcinogen) released from traditional plywood, particleboard, and other composite products. It was observed that the soya-based adhesive gave a better strength of the plywood when mixed with Plaster of Paris and some agro-based adhesive (called “Adhesive-A” in this article). This strength is further expected to increase by making the adhesive less viscous (and thus allowing it to fill the voids in the gluing surface), for which further experiments would be undertaken in the future.

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