INVESTIGATING PLASTINATION FEASIBILITY OF NATURAL FIBRES FOR IMPROVED DURABILITY

D. K. Dhir[1], B. Crawford[1], A. Rashidi[1], G. Bogyo[2], R. Ryde[2] and A. S. Milani[1]*
[1] Composites Research Network-Okanagan Laboratory, School of Engineering,
University of British Columbia, Kelowna, Canada
[2] Ryde Holdings Ltd., Penticton, Canada
* Corresponding author (abbas.milani@ubc.ca)

ABSTRACT

Plastination is a technique used for preservation of human and animal body organs for many years, by replacing the water and fat present in the tissues with a polymer. This work investigates the feasibility of plastinating natural fibres (here bamboo) using the S-10 room temperature technique to hinder their moisture absorption ability, and thus degradation. To this end, a plastination procedure was developed for application to natural fibres and its effect on the physical and mechanical properties and residual moisture content of natural fibres was evaluated. The results showed that as plastination lessens the hydrophilic tendency of natural fibres, it also decreases the residual moisture content in bamboo and increases its tensile strength and stiffness.

KEYWORDS*: Plastination, bamboo natural fibre composites, environmental durability*

1 INTRODUCTION

Due to growing concerns for environmental issues such as increasing manufactruing pollution, increasing carbon footprint, and raising awareness about the environmental hazards caused by man-made materials like synthetic fibre composites, great demand and interest for sustainable natural fibre composites have developed over time. There is a progression in industry to use natural fibres as fibres and fillers reinforced with polymers in place of synthetic fibres. Owing to their low density, low cost, high stiffness, and strength-to-weight ratio and improved sustainability, natural fibres are gaining a wide demand in particular in structural applications (Faruk et. al, 2012, Liu et al., 2014, Mohammed et al., 2015, & Pickering et al., 2016).

Among various natural fibres, bamboo is one of the most desirable options due to its low density and high strength properties. Furthermore, bamboo has over 1,450 species and the worldwhide bamboo production is approximately 30 million tons, the highest among all natural fibres (Faruk et. al, 2012, Liu et al., 2014, Mohammed et al., 2015). Despite the aforementioned desirable attributes of natural fibres, however, they are prone to degradation due to the effect of moisture and weathering.

In anatomical sciences, the long-term preservation of animal and human tissues has been carried out for over centuries and among the various preservation techniques used, plastination is a well-stablished technique. First applied in 1977 by Dr. Gunther Von Hagens, plastination, also called forced polymerization, has been extensively employed for preserving different bodies and body parts of living organisms (Rieder, 2014, Hagens, 1986, & Hagens 1979). In essense, plastination replaces the water and lipids in the tissue with curable polymers. It involves preserving perishable biological specimens using a series of procedures that replaces tissue water and part of tissue fat with curable polymers, mostly polyester, silicon and epoxy that hinders the decay of body tissue. Besides the wide range of applications of plastination techniques among human, animal and yeast tissues, there is no data if plastination could be possibly applied to preserve natural fibres, as a way to enhance the strength and durability of these fibres and their composites like bamboo fibre reinforced plastics (BFRP) (Jain & Kumar, 1994, Jain et al., 1992, Chand & Rohatagi, 1986). Furthermore, there is limited study conducted so far to validate the the residual moisture content in plastinated specimens and how they would behave when subjected to moisture. Despite the fact that BFRPs offer a low cost, there are several limitations such as lower modulus, and relatively poor moisture resistance, relative to synthetic fibres (e.g. glass fibers), due to the hydrophilic nature of these lignocellulosic fibres. Chemically altering the biological structure of these fibres could be one of the solutions to overcome the above limitations. The aim of the this work if investigate the feasibility of plastinating natural fibres (here bamboo) using the S-10 room temperature technique to hinder their moisture absorption ability, and thus degradation.

2 MATERIALS & METHODS

The specific bamboo specie that was primarily used for all of the following experiments was Inversa Bambusoide (also called 'Yellow Strip Timber'). It is a medium sized Asian timber bamboo that often grows to a height of around 35-45 feet with a culm diameter of 3 inches, smaller than the species which is recorded by the American Bamboo Society as growing to 60 feet with 5-inch diameter culms (Nursery, 2012).

Silicon plastination is one of the simplest and most versatile types of plastination involving silicone polymers as impregnation mixtures and hardeners. Among different silicone polymers, the S10 (polydimethylsiloxane) polymer is the most popular and widely used, and results in specimens that are opaque, and more natural looking. The S-10 technique comprises of four different steps; namely, fixation, dehydration, forced impregnation and curing (Hagens, 1986). The non-plastinated bamboo will be referred to as virgin bamboo hereafter. The first step of the S-10 standard procedure involves degreasing to remove lipids. However, in the present case, natural fibres did not possess much lipids and hence this step was skipped, and the process started with the second step; i.e. acetone dehydration.

2.1 Plastination procedure

2.1.1 Acetone dehydration

The idea behind acetone dehydration is to diffuse acetone into the cells to replace the existing water. To this end, the raw bamboo culms and fibre bundles were completely immersed in a 100% concentrated solution of acetone. The acetone container was placed in a deep freezer to maintain a temperature of -25^{0}C to prevent evaporation of volatile acetone, as shown in Figure 1. The acetone in the container was stirred once daily and the first acetone concentration check was done after 3 days of bamboo immersion. Unlike the bulky and complex human body parts that contain much higher aqueous content, the acetone concentration in the container after 3 days was greater than 99%. After ensuring the acetone concentration to be greater than 99%, the bamboo samples were taken towards the next crucial step of plastination; i.e. silicon impregnation.

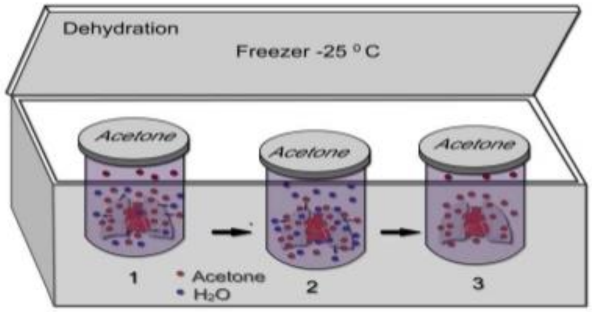

Figure 1: Acetone dehydration illustrative [Web-1].

2.1.2 Forced Impregnation

A room temperature impregnation process was followed in which high boiling point and low vapour pressure silicone mixture was impregnated into the cells of the specimens by vaporizing the low boiling point and high vapour pressure acetone. To achieve this forced impregnation level, the dehydrated samples from the acetone bath were quickly immersed into the silicone mixture. These samples were kept immersed in the silicone mixture overnight to achieve an equilibrium between the concentrations of acetone and silicone mixture. On the second day, the pressure chamber was sealed and pressure reduction inside the chamber was achcived using a vacuum pump through a catch pot. Initially, the pressure was decreased to 17.5" Hg and bubble formation was observed as the pressure decreased, as shown in Figure 2. The mixture was then allowed to withstand this pressure until no bubbles were observed on the surface. The vacuum was then further increased in a similar manner in increments of 4" Hg. The disappearance of bubbles assured that acetone has been removed within the bamboo and has been replaced by silicone. At around 28" Hg (close to perfect vacuum) the disappearance of bubbles was considered as the point of complete impregnation.

Figure 2: Formation of bubbles in silicone chamber due to pressure reduction.

2.1.3 Curing

After impregnation, the samples were cured using a spraying technique. The curing mixture was sprayed on the impregnated samples which initiated a cross-linking reaction between the S3 and S10 & S6 mixtures. The samples were later wrapped in a plastic wrap to ensure S3 was sealed and stayed in contact with the impregnated bamboo specimens.

2.2 Moisture conditioning

Five plastinated and virgin bamboo specimens were submerged in tap-water at 20±2°C (room-temperature) for 4 days. The duration, temperature and other test conditions were determined such that these parameters were consistent with the other on-going tests, as part of a larger study not described herein. The conditioned samples were then tested for density change, moisture and tensile strength. For all these tests, the samples were removed from the water container and wiped with a dry cloth to remove the excess water on the surface (Dhakal et al., 2007). These were then quickly tested per the required test procedures.

2.3 Density and Tensile testing

The density of the unconditioned and moistened plastinated and virgin bamboo samples was calculated to understand how plastination affected the moisture absorption (mass change) and swelling (volume change) in bamboo fibres. The determination of the moisture content of the wetted samples was done in accordance with ASTM D4442. This moisture content value provided insight regarding the nature of hydrophilic behaviour of plastinated samples as compared to non-plastinated (virgin) samples and their moisture desorption behaviour. Due to the lack of test codes for tensile testing of bamboo, a customized sample geometry was developed, with the rest of the test guidelines derived from ASTM D4761. This involved 4 x 4 mm sections of bamboo being extracted from the bamboo culm, with height equal to the maximum length of culm, about 120 mm (mostly uniform in all samples). The tensile strength parameters were then derived using the load-displacement curve generated during the tests. For this test, 12 replicates for each of the plastinated and virgin bamboo strips were conducted.

3 RESULTS & DISCUSSION

3.1 Effect of plastination on density

Figure 3 demonstrates that plastinated bamboo has about 57% higher density than virgin bamboo. This may be due to excessive silicone that flows into the bamboo fibers and substitutes the water. We can also observe that both virgin and plastinated bamboo have a density increase post-conditioning. This increase in density can be attributed to water absorption, owing to the hydrophilic nature of bamboo. Lesser increase in density of plastinated bamboo in comparison to virgin denotes the reduced moisture uptaking capability of plastinated bamboo. This, however, also signifies water occupying the internal voids of the cellular structure of plastinated bamboo, besides the presence of silicone at those sites. This discrepancy could be attributed to the high water vapour permeability of silicon which led water molecules to reach the bamboo cell wall and deteriorate it.

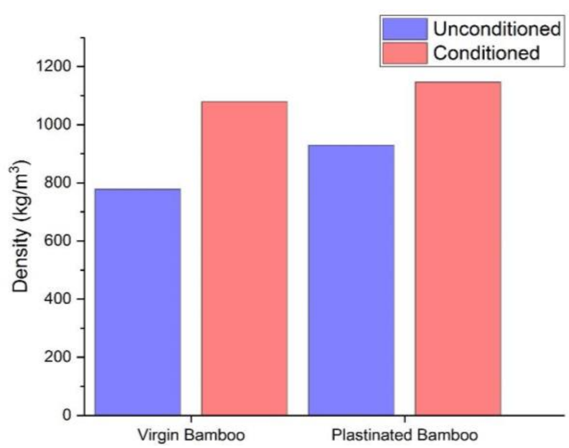

Figure 3: Density of virgin and plastinated bamboo, before and after moisture conditioning.

3.2 Effect of plastination on moisture behaviour

Figure 4 shows the experimental data on the moisture content of plastinated and virgin bamboo with an average moisture content of 109% for virgin bamboo. Plastinated bamboo also seems to have absorbed moisture during the water bath, but with an average moisture content of 95%. As aforementioned, a possible reason for this moisture gain may be the silicone's high permeability to allow water to reach the bamboo cell wall. This leads to an increase in the bound water and increased transport of bound and free water in bamboo cells as they absorb water following a Multi-Fickian moisture absorption model (Frandson, 2005). Further, a smaller desorption slope for plastinated bamboo as seen in Figure 4, denotes a lower desorption rate of water absorbed and trapped within the cellular bamboo and silicone.

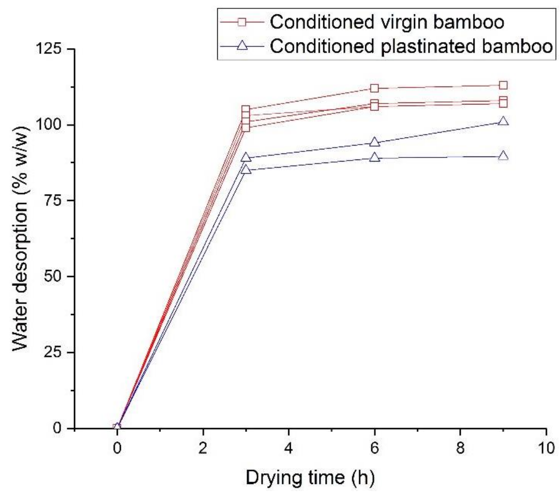

Figure 4: Weight fraction of water desorbed by virgin and plastinated bamboo vs. drying time in the oven.

3.3 Effect of plastination on tensile properties

From the data presented in Table 1&2, it is apparent that with a 70% increase in tensile strength and 22% increase in tensile modulus, plastination tends to add to the mechanical strength of bamboo. However, observing the decreased strain to failure in Figure 5, it is possible to hypothesize that after plastination, the impregnated silicone acts a matrix (interface) between the bamboo fibres and also occupies the voids in the hollow cellular structure, thus sharing and distributing the load more uniformly. And as the load approaches the failure limit, this binding matrix fails causing a sudden failure of the brittle bamboo fibres. With the increased strength and tensile modulus, the strain to failure drops by 47% in plastinated bamboo.

Table 1: Tensile strength comparison of different bamboo specimens tested

	Virgin bamboo (MPa)	Plastinated bamboo (MPa)	% Relative change
Unconditioned bamboo	128.5	219.5	%70.8 (increase)
Conditioned bamboo	62.5	108.3	%73.3 (increase)
% Relative change	%51.3 (decrease)	%50.7 (decrease)	

Table 2: Tensile stiffness comparison of different bamboo specimens tested.

	Virgin bamboo (GPa)	Plastinated bamboo (GPa)	% Relative change
Unconditioned bamboo	9.6	11.8	%22.9 (increase)
Conditioned bamboo	4.7	7.3	%55.3 (decrease)
% Relative change	%51 (decrease)	%38.1 (decrease)	

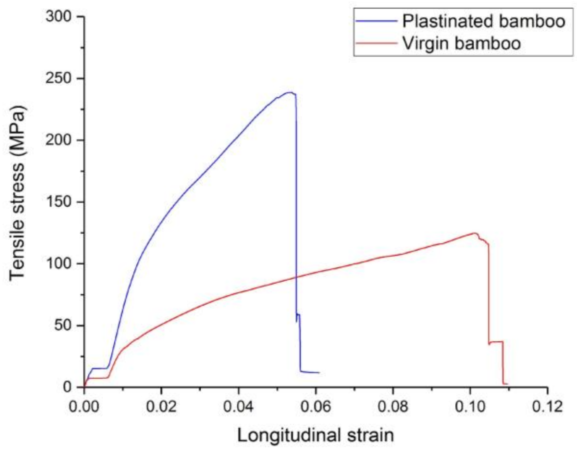

Figure 5: Tensile stress vs. longitudinal strain curves for the plastinated and virgin bamboos.

Table 1 further shows that moisture conditioning led to a 51.3% and 50.7% loss in strength of virgin and plastinated bamboo. These changes denote that both plastinated and virgin bamboo are affected by the moisture conditioning. Such reduction in strength of plastinated bamboo could be accounted to water vapour passing through the silicone and degrading the bamboo cell wall as water acts as a plasticizer to cellulose. However, Table 1 also shows that not only plastination increases the tensile strength of unconditioned bamboo, but even after moisture conditioning the tensile strength of plastinated bamboo is still 73% higher than virgin bamboo. Thus, it can be concluded that although moisture decreases the tensile strength of plastinated bamboo, plastinated bamboo still seems to be a much durable option overall as it can support greater loads under moisture.

Although the decrease in tensile strengths of conditioned virgin and plastinated bamboo is similar, a cross-comparison study from Table 1 illustrates that the final strength of conditioned plastinated bamboo is about 82% of the strength of virgin unconditioned bamboo. While, the tensile strength of virgin conditioned bamboo is only 28.4% of the tensile strength of unconditioned plastinated bamboo. Thus, even after moisture conditioning at elevated temperature, plastinated bamboo retains 82% of the tensile strength of original unconditioned bamboo.

In terms of stiffness, however, the fall in stiffness of conditioned plastinated bamboo is much lower at 38% as compared to 51% for virgin bamboo as shown in Table 2, as a result of plasticization. Moreover, the observation that conditioned plastinated bamboo provides 55% higher stiffness than conditioned virgin, definitely deems plastination suitable for bamboo processing to enhance its strength and stiffness in both moisture conditioned and unconditioned environments.

Further, a cross comparison of stiffness from Table 2 reveals that moistened plastinated bamboo has about 23% lower strength than unconditioned virgin bamboo while this percentage is 60% in case of virgin conditioned and unconditioned plastinated bamboo. Conditioned plastinated bamboo retains 77% of the strength of original bamboo as opposed to only 49% for conditioned virgin bamboo.

The fall in strength and stiffness of bamboo after conditioning may be explained by the fact that water presence dramatically softens the cell walls. During the plasticization of cellulose present in bamboo, by water, the hydrogen bonds between different polymer chains in cellulose can break. Subsequently, Hydrogen bonds form with water instead, as it is a small, polar molecule and hence can penetrate in between the polymer chains. Stronger hydrogen bonds are formed between cellulose and water than between cellulose and cellulose. This softens the cellulose micro fibrils as they are no longer so strongly bonded to each other. This leads to a decrease in the stiffness of bamboo. And as the water expands the cell wall, there are also fewer cellulose micro fibrils per unit area. Hence the strength of the bamboo decreases (Greer, & Pemberton, 2006)

The increased strain to failure of conditioned plastinated bamboo denotes plasticization of the semi-crystalline cellulose by water which decreases the tensile strength and stiffness with an increased the elongation to break due to increased ductility.

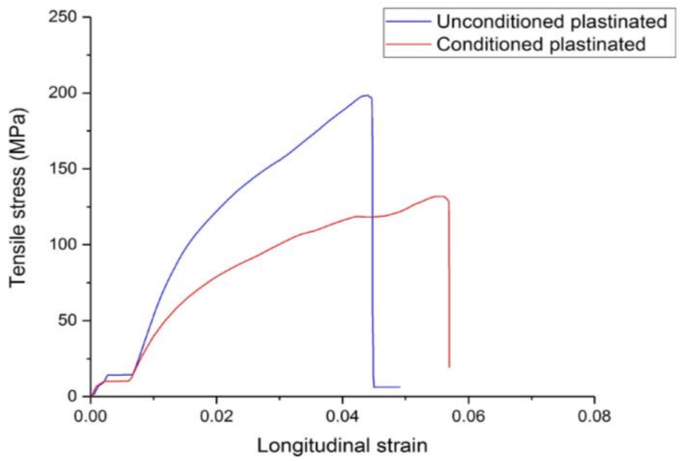

Figure 6: Tensile stress vs. longitudinal strain curves for plastinated conditioned and unconditioned bamboos.

3 CONCLUSION

This feasibility study showed that the S-10 plastination technique can be successfully applied to bamboo fibers. The tensile tests conducted denoted that plastination can significantly increase the strength and stiffness of the bamboo natural fibers. The moisture tests display that plastination leads to enhanced durability of bamboo under moisture conditioning and decreases its hydrophilic tendency to some extent. The absorption of moisture by plastinated specimens and their strength reduction post-conditioning suggests an important issue for further investigation to optimize/customize the plastination process for each given natural fiber type/specie.

4 ACKNOWLEDGEMENTS

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