Assessment of Natural Adhesives in Banana Leaf Composite Materials for Architectural Applications

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ABSTRACT
A preliminary investigation into natural adhesives for use in the manufacture of sandwich panels from banana plant wastes is reported. These panels, named MUSA panels, are designed as a low-cost construction material for rural communities in developing countries. Three natural adhesives – prepared from cassava starch (genus *Manihot)*, potato starch (*Solanum tuberosum*) and *Euphorbia tirucalli* latex – have been tested in addition to a PVA synthetic adhesive. Adhesive preparation trials, physico-chemical testing of adhesives and mechanical testing of adhesives bonded to dried banana leaves have been completed. The results of these limited tests show *Euphorbia tirucalli* latex adhesive to have the best mechanical properties and suitable physico-chemical characteristics. Recommendations are made for further work to confirm the suitability of the adhesive for MUSA panel applications.

Keywords: Banana, Green composite, Bio-adhesive, MUSA panel

1 INTRODUCTION

Rwanda is increasingly held up as a model of effective development in sub-Saharan Africa, but there remain high levels of poverty in the country. Traditional house building techniques in Rwanda include the use of timber, mud and grasses, and these materials are still employed in the construction of low-cost housing. Many modern houses are built using a reinforced concrete frame around walls of mud brick covered with a cement-based render and corrugated steel sheet roofing. However, these relatively expensive, imported materials are beyond the means of poorer communities. A novel composite sandwich panel made from waste banana plant materials has been developed to provide a good, low-cost building material that can be locally manufactured in rural communities. A preliminary investigation into locally available natural adhesives for use in the manufacture of these panels has been completed.

1.2 Green Composites

A composite is a material composed of two or more separate phases, having overall properties that are a combination of those of each phase. Natural Fibre (NF) composites, or "green" composites, have attracted much interest over recent years for engineering applications, particularly in the automotive industry, due to their good properties (high specific strength and high specific stiffness), low cost and an increasing focus on the use of renewable materials (van Rijswijk *et al.*, 2001). Most NF composites are produced by separation of fibres (retting), then incorporation of chopped short fibres into a synthetic polymer matrix using conventional composite manufacturing processes. In this type of composite, natural fibres are used as a substitute for synthetic reinforcements such as glass fibres.

"Truly green" composites may be defined as materials manufactured by incorporation of natural fibres into a "bio-polymer" matrix material derived from natural or renewable resources such as plant oils (Williams and Wool, 2000) or soy flour (Chabba *et al.*, 2005). The main attraction of truly green composites is environmental: they are considered to have no impact on global warming as, even when incinerated; the volume of CO_2 released equals that consumed by the crop before harvesting (Bismarck *et al.*, 2006).

Sandwich panels are a class of composite material consisting of two outer faces (or skins) separated by, and adhesively bonded to, a thicker core. This is a quite different construction to that of fibre-reinforced composite materials. Sandwich panels are typically manufactured to provide a combination of relatively high stiffness, strength or impact resistance in the face material(s) with a low density, thermally insulating or acoustically insulating core material. There is very little in the literature on sandwich panels manufactured from natural materials.

1.3 MUSA Panels

The current work relates to novel sandwich panels, named MUSA panels, constructed from banana plants using pieces of dried "bark" (or "leaf") to form the faces, and short sections of transversely-orientated dried "stem" in the core, as shown in Figure 1 and Figure 2. The components are adhesively bonded together. The MUSA panel was designed by researchers at the University IUAV of Venice, Italy as a truly green composite that can be manufactured easily and cheaply from readily available materials to improve standards of housing. MUSA panels are designed as non-load-bearing interior wall and insulation panels for construction of rural housing in Rwanda and other developing countries (Morpurgo, 2010-1; 2010-2).

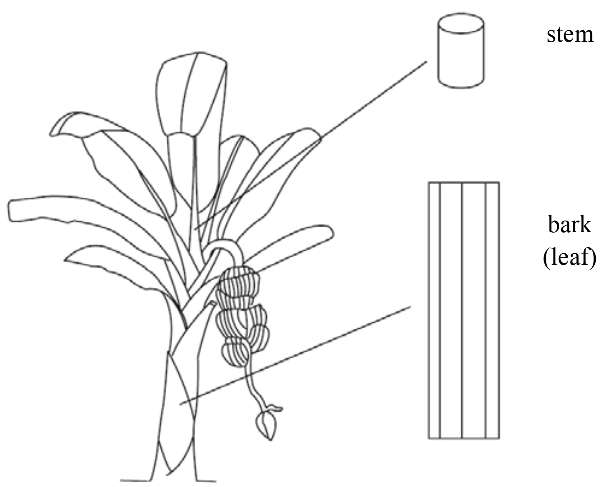
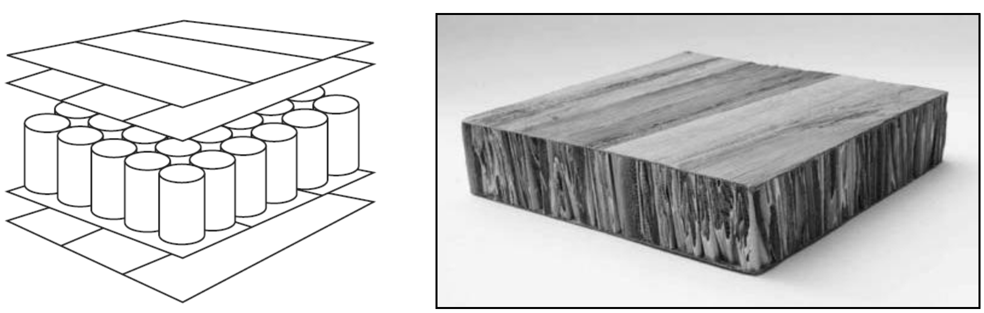


Figure 1: Sources of sandwich panel components from a banana plant (Morpurgo, 2009-1)



(a) (b)

Figure 2: MUSA panels – (a) construction; (b) prototype panel (Morpurgo, 2009-2)

Banana plants (genus *Musa*) are abundant in Rwanda and many other developing countries in the tropics. Each plant produces a single stem of fruit and, after harvesting, the plant is cut down and discarded. Therefore, the faces and core of the MUSA panel are made from waste materials. To realise the potential of MUSA panels it is also necessary to identify a low-cost natural adhesive ("bio-adhesive"), widely available in Rwanda, for use in panel manufacture. Prototype MUSA panels (Figure 2) have been made using a polyvinyl acetate (PVA) synthetic adhesive, VINAVIL®, and shown to provide effective thermal and acoustic insulation (Morpurgo, 2010-1). A panel density of 165kg/m^3 is reported, as well as thermal conductivities of 0.043 and 0.063 W/mK for panels of 30mm and 50mm thickness, respectively (Morpurgo, 2009-1).

2. MATERIALS AND METHODS

2.1 Adhesives and Their Preparation

Bio-adhesives have been prepared from three natural materials: cassava starch (genus *Manihot)*, potato starch (*Solanum tuberosum*) and latex of the shrub *Euphorbia tirucalli*. A PVA synthetic adhesive (WoodFix from Falcon Chemicals) has also been tested for comparison.

The cassava starch and potato starch adhesives were each prepared by mixing 2.5g of ground flour with 50ml of dilute hydrochloric acid (0.01M HCl in H_2O) whilst heating to 94°C (Ozemoya *et al.*, 2007). *Euphorpbia tirucalli* latex was extracted by cutting stems of the shrub and collecting the secreted latex emulsion, in a similar manner to tapping of natural rubber. To prepare the adhesive, 15ml to 25ml of latex was mixed with 2g of palm oil and stirred whilst heating to 75°C.

2.2 Physico-Chemical Testing

Three samples of each natural adhesive were prepared for physico-chemical tests. The dynamic viscosity of each adhesive sample was measured at elevated temperature (the relevant formation temperature for each adhesive) using a Haake viscometer. The pH of each adhesive sample was measured using a pH meter at the formation temperature. The stability over time of one sample of each adhesive was assessed at the formation temperature by regular measurement of viscosity; when the viscosity was found to have changed, the stability limit (in hours) was judged to have been reached. The cure time for one sample of each adhesive was assessed qualitatively by pasting a layer of adhesive between two pieces of dried banana leaf, then judging when a significant adhesive force developed between the two.

2.3 Mechanical Testing

Tensile testing to failure for each adhesive was carried out using specimens (Figure 3) manufactured from 3 layers of dried banana leaf bonded together with the relevant adhesive, and cured for at least 24 hours under a compressive load. The gauge length of specimens was 120 mm; thickness varied between 3.4 and 5.8 mm; width in the gauge length varied between 7 and 10 mm. Load and elongation were recorded during testing and used to calculate stress and strain. The strain rate during testing was approximately 0.0005 s^{-1}. Tensile testing was also carried out on single dried leaves, for which thicknesses were 0.8 to 1.2 mm.

Shear testing to failure of each adhesive was carried out using lap joint specimens (Figure 3). Half specimens manufactured from two layers of dried banana were bonded together with the relevant adhesive to form a lap joint. Testing was carried out at an extension rate of ~0.05mm.s^{-1}. Shear stress (τ, MPa) was calculated from the maximum recorded load (P, N), overlap joint width (b, mm) and overlap joint length (L, mm) using Equation (1). The failure path (whether through the adhesive or an adjacent layer of banana leaf) was noted.

$$\tau = \frac{P}{bL} \tag{1}$$

$$Peel\ strength = \frac{P}{w} \tag{2}$$

90° peel tests were carried out using specimens manufactured from a single layer of dried banana leaf bonded along half of its length to a stiff base panel of three layers of leaf. The bond line width for each specimen was in the range 35 to 40mm. Testing was carried out at an extension rate (in the direction of the tensile force) of ~0.1mm.s^{-1}. Peel strength (N.mm^{-1}) was calculated from the maximum recorded load (P, N) and the bond line width (w, mm) using Equation (2). The failure path (whether through the adhesive or the adjacent leaf) was noted.

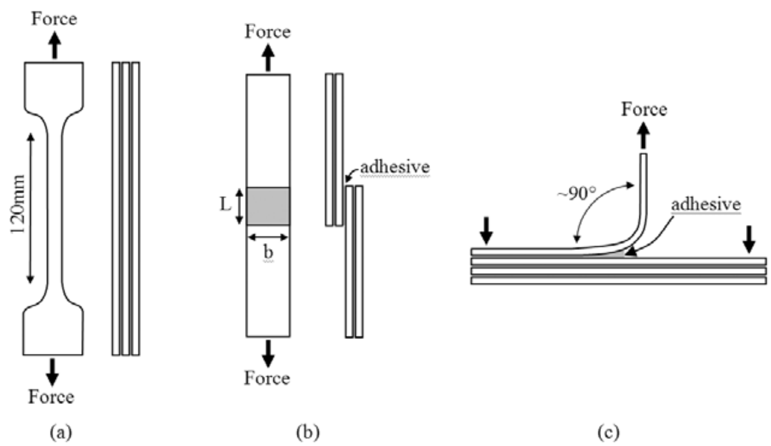


Figure 3:Mechanical testing specimen diagrams, (a) tensile tests, (b) shear tests, (c) peel tests; not to scale; multiple layers of leaf were bonded together using the relevant adhesive.

Mechanical testing specimen types are shown in Figure 3. Primary fibres in the banana leaves were orientated longitudinally with respect to the applied tensile stress in all layers. All mechanical tests were performed using a Universal Testing Machine (UTM). The results of testing are regarded as indicative only as the UTM had a high capacity load cell that could not accurately measure the small loads applied to these specimens, and tests were not performed in strict accordance with national or international testing standards.

3. RESULTS AND DISCUSSION

3.1 Physico-Chemical Testing

The results of physico-chemical testing are shown in Table 1. No correlation was found between volume (weight) of raw material used in adhesive preparation, viscosity and pH. Temperature is the main factor that affects viscosity; across all four adhesive types viscosity is inversely proportional to temperature. For each adhesive, pH was found to be inversely proportional to viscosity, but no general correlation was found across all adhesive types.

Table 1: Physico-chemical test results

Adhesive Type	Formation Temp (°C)	Mean Viscosity (cP)	Mean pH	Cure Time (min)	Stability Limit (hours)
Cassava Starch	92	31536	5.1	5	24
Potato Starch	94	30656	6.0	5	24
Euphorbia Latex	75	35265	5.6	2	36
Synthetic (PVA)	25	28565	6.8	5	-

The relatively high viscosity, short cure time and greatest stability limit suggest that the *Euphorbia* latex preparation is best suited to the adhesive application.

3.2 Mechanical Testing

Typical stress-strain curves produced from tensile test results are shown in Figure 4. Single-layer leaf specimens failed completely at the maximum stress. Composite specimens generally failed progressively, retaining some strength beyond the point of maximum stress.

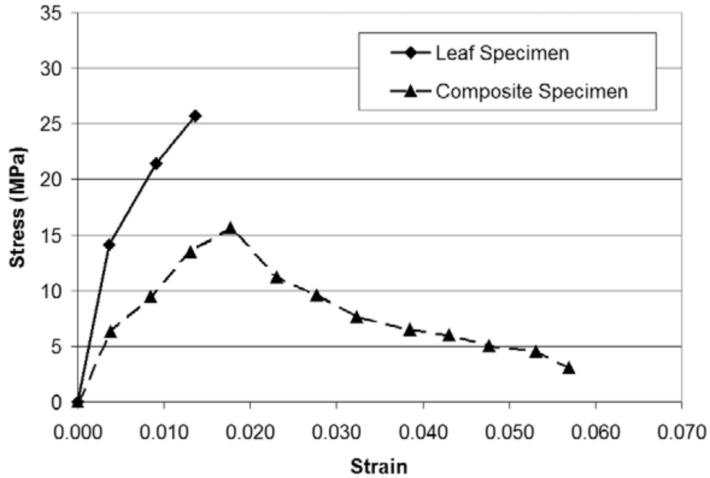


Figure 4: Typical stress-strain curves for leaf and composite specimens

Mechanical testing results are shown in Table 2. For tensile testing the tensile strength (σ_{TS}), that is the maximum stress, is reported with the strain at the point of maximum stress (ε at σ_{TS}). The strain to *complete* failure of composite specimens is not shown, but varied greatly between specimens, even for the same adhesive. For shear tests, the shear strength (τ) is presented with comments on the failure path. It was found that the testing equipment was not sufficiently sensitive to record useful results from peel tests, so comments on failure path are shown, but peel strength is not. No tests were performed on potato starch specimens.

Table 2: Mechanical test results

Specimen Type	σ_{TS} (MPa)	ε at σ_{TS}	τ (MPa)	Shear failure path comments	Peel failure path comments
Banana Leaf	23–32	0.010–0.023	-	-	-
Banana Leaf / Cassava Starch	10–18	0.018–0.023	0.14–0.20	Some tests failed through adhesive, some in leaf	Some tests failed through adhesive, some in leaf
Banana Leaf / Potato Starch	-	-	-	-	-
Banana Leaf / *Euph.* Latex	17–19	0.009–0.025	0.44–0.65	All tests failed through leaf	All failed partly through adhesive and partly in leaf
Banana Leaf / PVA	11–18	0.009–0.021	0.44	All tests failed through leaf	All tests failed through adhesive

Tensile test results show that the banana leaf alone is stronger in tension that the composite specimens. Measured tensile strengths of banana leaves are significantly lower than strengths of single banana fibres reported in the literature which range from 85 MPa (Al-Qureshi, 1999) to 750MPa or more (Murali Mohan Rao *et al.*, 2007; Kulkarni *et al.*, 1983). This is because only part of the cross-sectional area of each leaf consists of fibres; a large proportion is air. Retention of some strength beyond the maximum stress in composite specimens suggests that composite MUSA panels will have greater damage tolerance than dried banana leaves alone.

Shear test results show that the shear strength of the *Euphorbia* latex lap joint was greater than that of the synthetic adhesive, which was greater than that of the cassava starch. When considering specimen failure, if the failure path was through the adhesive, no assessment was made as to whether it was the adhesive or of the adhesive/leaf bond that failed. Cassava adhesive specimens failed either through the adhesive or through the adjacent leaf, suggesting that the shear strength of the adhesive (or the adhesive/leaf bond) is similar to that of the dried leaf. All *Euphorbia* latex and synthetic adhesive specimens failed through the leaf, suggesting that the shear strength of the adhesive (*and* the bond) is greater than that of the leaf. For adhesive use in MUSA panels, it is undesirable for specimens to fail through the adhesive (or at the bond) as this suggests that the shear strength of the composite panel would be limited by that of the adhesive and so not take full advantage of the strength of the leaf.

Peel failure paths in the cassava adhesive and *Euphorbia* latex specimens suggest that the strengths of these adhesives (or adhesive bonds) under this type of loading are similar to the strength of the dried banana leaves, whereas the failures of the PVA specimens suggest that the adhesive (or bond) strength is lower than that of the leaf. For the MUSA panel application, it is undesirable for the peel tests to fail through the adhesive as this suggested that the peel strength of the panel would be limited by the adhesive, not the leaf.

Mechanical test results suggest that *Euphorbia* latex is the most suitable adhesive due to its superior tensile strength, shear strength and failure characteristics in both shear and peel, and it performs better than a PVA adhesive similar to that used in prototype panels. The properties tested are relevant to the MUSA panel application. However, further mechanical tests on complete panels under compression and impact loadings would be valuable.

3.3 Discussion

The testing has shown that the hydrophilic properties of many natural fibres (including banana) that can lead to bonding problems with synthetic polymer matrices and a resultant need for suitable pre-treatment of fibre surfaces – see Nabi Saheb and Jog (1999), El-Meligy *et al.* (2004), Kalia *et al.* (2009) – do not present a concern for manufacture of MUSA panels.

Because the MUSA panel is not a highly engineered application with onerous property requirements, concerns about variability in the properties of natural materials (see, for example, van Rijswijk *et al.*, 2001; Bismarck *et al.,* 2006; Holbery and Houston, 2006) are not relevant so long as the undemanding properties that are adequate for this application can consistently be achieved. This can be demonstrated through qualitative field trials of panels.

4. CONCLUSIONS

Preliminary work to assess the potential of a limited number of natural adhesives for use in the manufacture of MUSA panels has been completed. From the results of adhesive preparation trials, physico-chemical testing of adhesives and mechanical testing of adhesives bonded to dried banana leaves, an adhesive prepared by mixing *Euphorbia tirucalli* latex with additions of palm oil whilst heating was found to provide the most best mechanical properties and suitable physico-chemical characteristics. It is recommended that further work is undertaken to investigate fully the suitability of this adhesive in the MUSA panel application.

5. RECOMMENDATIONS AND FURTHER WORK

It is recommended that adhesive prepared from *Eurphorbia tirucalli latex* is provisionally selected for use in the manufacture of MUSA panels, and that further work is done to develop the adhesive and fully demonstrate its suitability, including:

- Assessment of the costs and feasibility of latex collection and adhesive preparation.

- Assessment of toxicity hazards to humans and domestic animals presented by collection, preparation and service of the *Euphorbia tirucalli* latex adhesive, including potential for leaching from MUSA panels and assessment of exposure control measures.
- Mechanical testing of complete MUSA panels.
- Confirmation that conclusions drawn from testing of dried banana leaf face materials also apply to dried banana stem core materials in the composite sandwich panel.
- Assessment of degradation (due to moisture, UV light, insect attack) and fire performance of panels. These are issues cited in literature for NF materials (*e.g.* van Rijswijk *et al.*, 2001; Nabi Saheb and Jog, 1999; Holbery and Houston, 2006).
- If required, selection of low-cost, natural insecticide, fire retardant and moisture sealing treatments and assessment of effects of these on adhesive and panel properties.

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