EFFECT OF ENVIRONMENTS ON THE STABILITY OF EPOXY-BASED ADHESIVE FOR BONDED-IN TIMBER CONNECTIONS

Z. Ahmad[a], M. P. Ansell[b] and D. Smedley[c]

[a]Faculty of Civil Engineering, University Technology Mara Malaysia,
40450 Shah Alam, Selangor, Malaysia
[b]Materials Research Centre, Department of Mechanical Engineering, University of Bath, BA2 7AY, United Kingdom
[c]Rotafix (Northern) Limited, Rotafix House, Abercraf, Swansea, SA9 1UR, United Kingdom
Email: zakiahah@hotmail.com

ABSTRACT

The environment stability of three epoxy-based adhesives modified with nano-rubber and micro-ceramics particles additions, specially formulated for in-situ bonding of pultruded rods into timber were evaluated after exposure to 50°C at 95%RH for 90 days. The tensile strength and glass transition temperature of the bulk adhesives were assessed. The bond strengths were measured using pull-out tests of bonded-in pultruded rods and block shear tests across bonded gluelines. The nano-particles filled adhesive is able to resist the negative effect of environment on tensile strength and has a lower reduction in shear strength in block shear tests and pull-out tests compared to the other adhesives. The micro-filled epoxy formulation retains high shear strength and Modulus of Elasticity with very low elongation at break and significantly improves glass transition temperature.

Keywords: nano- and micro-fillers, mechanical properties, environment, bonded-in timber connections, bonding strength.

1. INTRODUCTION

Bonded-in rods have been used for the repair and upgrading of existing timber structures and in new construction for at least 30 years (Avent, 1986 and Riberholt, 1988). Although they are still considered a "new technology", the basic rules for the mechanical performance and design of this kind of joint have been defined (Townsend, 1990). There are number of factors that have to be considered in the design of adhesive-bonded connection which include moisture content (MC) of the timber, characteristics of adhesives, connection configurations, types and sizes of pultruded rods and operating environments (Ansell and Smedley, 2007, Joseph, 1999, Davis and Claisse, 2001 and Broughton and Hutchinson, 2001). Bonding of rods into timber members has been investigated by Broughton and Huchinson (2001), whom indicated that efficient, high strength joints can be made with epoxy resin adhesives due to their capability to produce thicker gluelines. They also explored the effect of key parameters (adhesive type and performance, rod embedment length, rod diameter, annular bondline thickness, multiple rods and rod spacing) on bonded-in joint performance using both experimental and numerical techniques and found that pull-out strengths can be significantly improved through careful selection and optimization of the joint geometry. These studies were focus more on perfecting the connection design, however less attention was given on the properties of the adhesive used. Among the studies used, connection made using CB10TSS showed superior performance. However, CB10TSS has Tg of 31.7°C and is considered low for service temperature. Although these adhesives have been used in construction, these adhesives may perform below their ultimate capabilities due to lack of information on their performance beyond room temperature condition. The lack of structural durability of epoxy adhesives bonded to wood has always been a problem for fabricators of adhesive-bonded wood products for service in exterior environments. Broughton and Hutchinson (2001) investigated the effect of timber MCs (at time of bonding) on bonded-in rods and found that the MCs in excess of service class 2 (SC2) (i.e. above 22% at the time of bonding), exhibited reduced strengths irrespective of the epoxy or rod typed used. However in their investigation, the Timberset adhesive, manufactured by Rotafix, appeared to be less sensitive than the other commercial adhesives to the different MCs used. This is may be due to the addition of nano-fillers in the epoxy adhesives formulation. In previous work by the authors (Ahmad *et al.*, 2006), CB10TSS was modified by adding nano- and micro-particles and found that the additions of nano filler (liquid rubber) has improved the tensile strength of CB10TSS by 36% and the addition of micro-fillers has increased the Modulus of Elasticity by more than 300% however reduces the tensile strength by 23%. As the additions of nano- or micro-fillers have shown to improve the mechanical properties of the adhesives, therefore it is also expected to improve the durability. Therefore the main aim of this research was to investigate the effect of nano- and micro-filler additions on the environment stability of adhesively-bonded joints.

2. METHODOLOGY

2.1 *Materials*

2.1.1 *Adhesives*
CB10TSS is a commercialized adhesive obtained from Rotafix Ltd and this adhesive is a high-viscosity, two-

phase epoxy adhesive system consisting of Part–A (epoxy adhesive mixture of diglycidlyether of bisphenol-A (DGEBA) with reactive diluent glycidlyether (monofunctional) and silica fume nano-particles (7.6 weight %) for thixotropic characteristics) and Part-B (hardener, mixture of polyetheramines) and this mixture (CB10TSS) is considered the standard adhesive. The other two adhesives were formulated from standard adhesive but with the addition of either liquid rubber (carboxyl-terminated butadiene and acrylonitrile (CTBN) at 2.0 weight %) or micro-particles (a mixture of bentonite, quart and mica at 56 weight%). These adhesives were designated as CB10TSS (standard adhesive), Albipox (standard adhesive/rubber) and Timberset (standard adhesive/bentonite, quartz and mica).

2.1.2 Timber

Kerto laminated veneer lumber (LVL) panel, manufactured from Norwegian spruce veneer, was selected for its consistent mechanical properties and it had an initial moisture content of approximately 10% by weight. The LVL was used for block shear tests and pull-out tests with bonded-in rods.

2.2 Preparation of specimens and experimental measurements

2.2.1 Tensile tests on adhesives

The tensile specimens were prepared in a dumbbell shaped aluminium mould as specified in ASTM D638 (1991). A glass plate was placed on top to provide a flat finish.

The tests were performed with an Instron 1185 Universal Testing Instrument equipped with a 100 kilo-Newton (kN) load cell and a 25 mm gauge length extensometer was used at mid-span for strain measurements. The tensile load was applied at a displacement rate of 5 mm/min. Ten samples of each type of adhesive were tested. The tensile strength, strain at failure and the elastic modulus were measured.

2.2.2 Differential Scanning Calometry (DSC)

The glass transition temperature and the stability of the cured adhesive were determined using differential scanning calorimetry (DSC) using a TA Instruments differential scanning calorimeter, Model 2910 with a controlled cooling accessory. A cured adhesive sample was cut as a disc with a mass between 10 to 20mg and was placed in a closed aluminum pan. The samples were scanned from 20°C to 180°C at a constant rate of 2°C/min and then air-cooled.

2.2.3 Block shear of bonded interface

The block was prepared from 50 mm thick laminated veneer lumber (LVL) panel which was sliced into two parts in the plane of the veneer (avoiding glue lines

between veneers) to make two beams, one 22 mm thick and the other 25 mm thick. The LVL adherends were laid side by side. Two Perspex shims of 3 mm thickness were placed at the end of the beam as thickness guides. An aluminium plate was attached with brown tape to the bottom of the mould to prevent the adhesive from leaking out. The adhesive was poured and spread slowly onto one of the adherends. Then the other adherend was place on top. The wood composite was clamped together by binding it with brown tape and also by using steel clamps to secure the bonding. The composite was left to cure at room temperature for 10 days and then the LVL adherends were trimmed at the edges to remove the aluminium plate and the shims. The beam specimens were cut into 50mm x 50mm x 50mm blocks in such away that one adhesive to LVL interface was subjected to shear (see Figure 1).
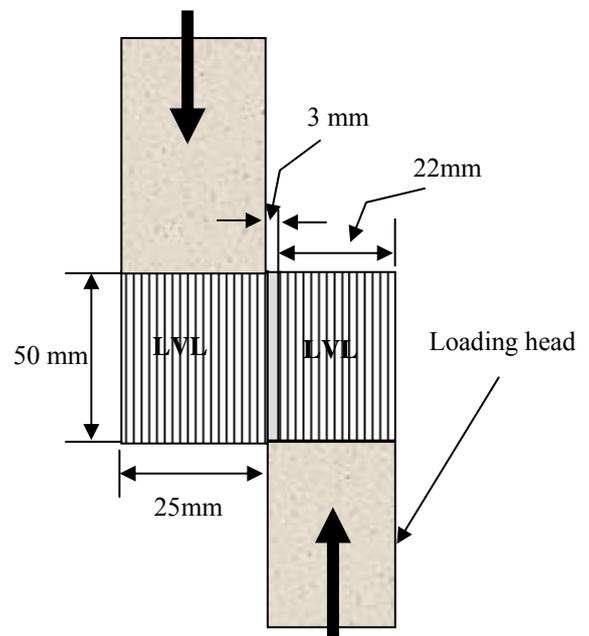

Figure 1: Test set-up for block shear test: schematic diagram of loading head.

Ten replicates were randomly chosen per adhesive formulation. After a further 10 days of room temperature curing, the test specimens were stored in a humidity room kept at a temperature of 50°C and 95% RH until the time of testing. The shear specimens were tested according to ASTM D905. The shearing load was applied using an Instron 1185 test machine with a 100 kN laod cell, with a continous motion of the crosshead at 0.5 mm/min until the maximum load was reached. The shear strength was calculated.

2.2.4 Pull out of bonded-in rod

The 63 x 63 x63 mm LVL block was drilled to make 12 mm diameter holes. The inner surface of the hole was lightly sanded in order to improve bonding by the removal of loose wood fibre. The glass fibre reinforced plastic rod of 8 mm diameter was also lightly surface abraded and cleaned with ethanol before inserting into the hole filled with adhesive resulting in a 2 mm annular

bond line thickness (See Figure 2). An O-ring was placed at the top and bottom of the hole in order to centre the rod. The bonded-in timber specimens were left to cure in a controlled humidity room for 20 days.
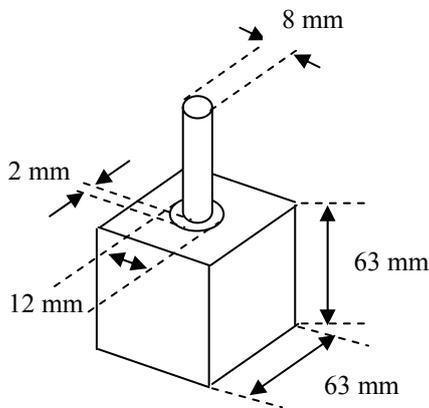

Figure 2: Single-ended pull-out test specimen

Figure 3: Experimental set-up for pull out test.

After conditioning the specimens were tested in tension using an Instron 1185 test machine with a 100 kN load cell, using a steel caged jig (see Figure 3). The timber blocks were positioned within the cage, with the rod protruding through a hole that had been machined out of the base plate of the jig. The base of the cage acted as a reaction plate against the timber block as the rod was pulled through the hole at a constant cross-head displacement rate of 2 mm/min.

2.2.5 Moisture absorption test

Plates of adhesive, 2 mm thick, 500 mm wide and 500 mm long were prepared in a mould from the CB10TSS, Timberset and Albipox adhesives as shown in Figure 4. The adhesive was left in the mould for 6 days to cure. After demoulding, the adhesive plate was cut using diamond cutter for the moisture up-take test specimens in accordance with BS EN 2243-5:1992: Standard test methods for structural adhesives – Part 5: Ageing tests. The adhesive specimens were exposed to humid environment namely 20°C/95%RH and 50°C/95%RH. Moisture uptake was measured by recording the weight change before and after exposure as a function of time.
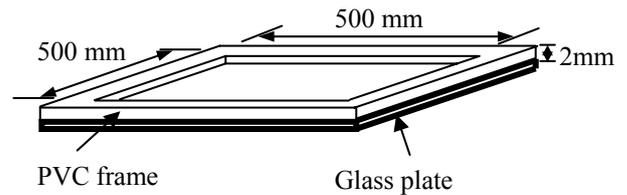

Figure 4: Mould for bending specimen

The moisture absorption characteristics of the adhesives were also determined by gravimetric measurements given by Equation (1).

$$M_t = \frac{m_t - m_o}{m_o} \, x100\% \qquad (1)$$

where M_t is moisture uptake at any time t, m_t is the mass of the specimens at any time t during ageing and m_o is the oven dry mass of the specimen.

2.2.6 Ageing environment and test schedules

After 20 days curing the tensile, block shear and pull out specimens were aged in an environmental cabinet conditioned at 50°C and 95% RH. After periods of 1, 2 and 3 months, the specimens were removed for testing.

2.2.7 Scanning Electron Microscopy

The fracture surface of adhesives was inspected in a JEOL JSN6310 scanning electron microscope (SEM) equipped with a computer image analysis system, after gold coating.

3.0 RESULTS & DISCUSSION

3.1 Tensile strength

During the tensile test, initial linear behaviour was followed by plastic yield of CB10TSS and Albipox after ageing in the high temperature and high humidity environment until the ultimate strength was reached. The extensometer was removed when the material behave plastically even though the ultimate capacity had not been reached. This was because beyond this point the extensometer would have exceeded its range of travel. However, loading was continued until failure to determine the ultimate tensile stress. The percentage of elongation was measured manually if the specimens deformed plastically. Two marks were created on the tensile specimen, 25 mm apart, and described as the gauge length, *Lo*. After fracture the specimens were put back together and the length between two markers were taken and denoted as the final length at fracture, *L*. The percentage of elongation was determined by:

$$\% \text{ elongation} = \left(\frac{L-L_0}{L_0}\right) \times 100 \qquad (2)$$

The tensile strength, modulus of elasticity and elongation at break properties of all the adhesives (CB10TSS, Albipox and Timberset) after 30, 60 and 90 days exposure at 50°C and 95% RH are shown in Figures 5 to 7, respectively and the tensile properties at 20°C and 65% RH and after 90 days of exposure to 50°C and 95% RH is presented in Table 1.
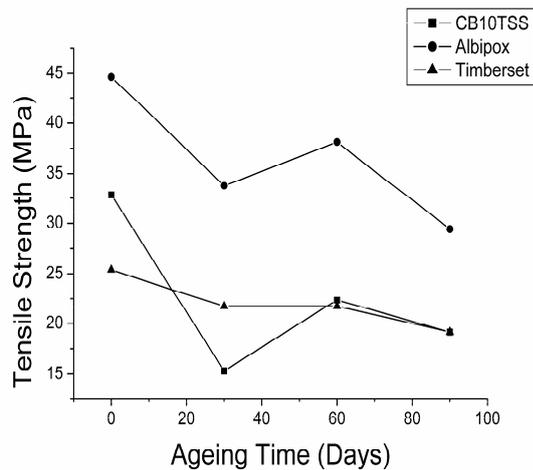

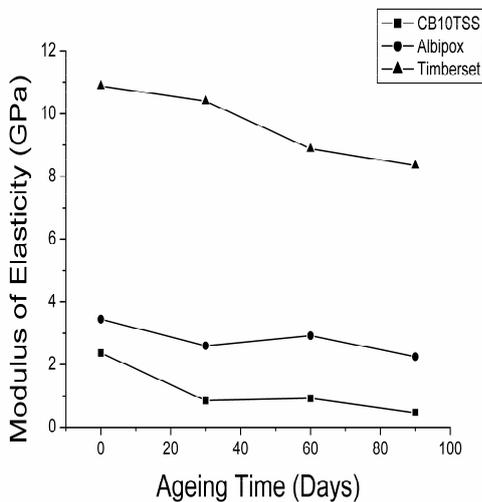Figure 5: Tensile strength as a function of ageing time for adhesives aged at 50°C and 95% RH

Figure 6: Modulus of Elasticity as a function of ageing time for adhesives aged at 50°C and 95% RH

Curve fits have been drawn through the mean values for convenience, but are not meant to imply accurate trends. In general, the aged samples for all three adhesives show reduction in tensile strength and Modulus of Elasticity and an increase in the failure strain. The overall trend is for the tensile properties to change significantly in the initial 30 days with the tensile strength going down and

the failure strain going up. Then the tensile strength for CB10TSS and Albipox showed some recovery after 60 days before they finally decrease again. However, Timberset showed a steady decrease in tensile strength with time of aging.
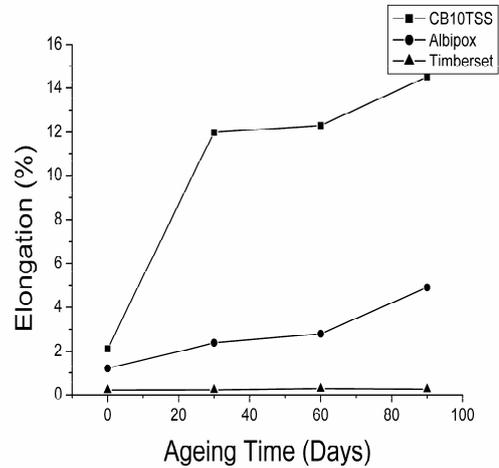

Figure 7: Elongation as a function of ageing time for adhesives aged at 50°C and 95% RH

Reduction in the tensile strength and increase in the failure strain of the adhesives upon exposure to hot/wet environment can be attributed to the plasticization of the adhesive materials caused by moisture absorption. In order to explain this phenomenon, the moisture absorption characteristic of these adhesives was obtained. Results from the absorption measurements were plotted as moisture uptake, M_t versus the square root of time ($t^{1/2}$). Figure 8 shows the absorption curves for CB10TSS, Albipox and Timberset after ageing at 50°C/95%RH. Each point on the curves represents the average of three specimens. The time of conditioning for each condition varies between 3 and 6 months. The experiments were stopped when the specimens reached the equilibrium state. The absorption of moisture was not accompanied by any visible damage to the material except colour changes (yellowish) in the case of CB10TSS aged at 50°C/95%RH.

From Figure 8, it is seen that Timberset exhibits a smooth increase in moisture absorption up to a stable saturation level that is reached after about 1600 hours. This characteristic reflects in the gradual decrease in tensile strength of Timberset as seen in Figure 5. However, the moisture absorption characteristics for CB10TSS and Albipox are fluctuating after 625 hours (approximately 30 days) which also correlates well with the up and down in the tensile strength of the adhesives. There are numerous physical and chemical mechanisms that could be considered responsible for this behaviour. The rapid first stage of moisture uptake may be mainly attributed to the diffusion of water molecules into the pre-existing free volume in the materials which correlates well with the abrupt reduction in strength.

Table 1: Results for tensile specimens tested at 20°C and 65% RH and after 90 days ageing at 50°C and 95% RH

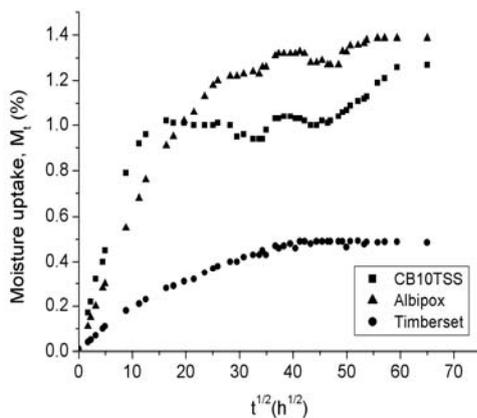| Variable	Control (20°C and 65% RH)		
	CB10TSS	Albipox	Timberset
Tensile strength (MPa)	32.83 ± 1.85	44.64 ± 0.45	25.40 ± 1.60
Modulus of Elasticity (GPa)	2.37 ± 0.23	3.44 ± 0.01	10.88 ± 1.38
% Elongation	2.12 ± 0.23	1.2 ± 0.11	0.21 ± 0.02
	50°C and 95% RH		
	CB10TSS	Albipox	Timberset
Tensile strength (MPa)	19.14 ± 2.62	29.43 ± 1.48	19.16 ± 4.12
Modulus of Elasticity (GPa)	0.47 ± 0..02	2.25 ± 0.29	8.35 ± 0.96
% elongation	14.50 ± 1.24	4.89 ± 0.37	0.25 ± 0.02

Figure 8: Moisture absorption curves for adhesives aged at 50°C/95%RH.

On the other hand, the second stage of moisture uptake may be a consequence of a relaxation process in the materials or chemical interaction between the polymer and absorbed molecules (Moy and Karasz, 1980). The up and down moisture uptake may be caused by fluctuating swelling stress as well as the retardant moisture uptake process produced by the presence of the fillers to matrix interphase zone (Hoh *et al*, 1990).

The slight recovery in the tensile strength for CB10TSS and Albipox implies that further crosslinking or other mechanisms, which enhance the material strength, may occur during aging. However, temperature also increases the rate of diffusion and this might cause some changes in the diffusion rate through regions of low density and higher density as the adhesive post-cures, thus causing the up and down in the tensile strength of the CB10TSS and Albipox.

Albipox has a higher tensile strength throughout the aging period, while CB10TSS and Timberset have much lower strengths. CB10TSS has the highest reduction in strength (42%) followed by Albipox (34%) and Timberset (25%). As for strain at failure, CB10TSS shows the highest increase in strain at failure (more than 500%), followed by Albipox (more than 200%) and Timberset with a very small increase (19%).

Figure 9 shows the difference in length for CB10TSS and Albipox after aging. This phenomenon may be explained from the consideration of the kinetics of water diffusion.
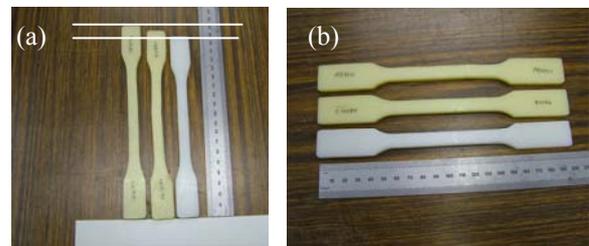

Figure 9: Tested tensile specimens before and after exposure to 50°C and 95% RH. (a) CB10TSS and (b) Albipox

As the glass transition temperature for CB10TSS (31.73°C), is very much below the aging temperature, water may readily diffuse into the adhesives and plasticize the material during aging. On the other hand, Albipox (Tg=42.82°C) and Timberset (Tg=53.81°C) possess slightly higher glass transition temperatures which are close to the conditioning temperature so molecular movements are restricted compared to CB10TSS. Therefore the rate of water diffusion into Albipox and Timberset will be restricted with a more rigid chemical structure compared to CB10TSS. As a result, the tensile strength and modulus for Albipox is less affected by water ingress compared to CB10TSS aged for the same period of time. It was also found that for Timberset, after 90 days aging, the strain to failure was slightly decreased. The reduction in strength and modulus of epoxy-filled adhesives may be due to both matrix plasticization and debonding at filler to matrix interfaces. Figures 10a and 10b show micrographs of unaged and aged tensile fracture surfaces of Timberset. The aged sample is flatter and there is an indication of some debonding and matrix cracking. Thus the reduction in the failure strain as well as tensile strength after 90 days ageing may be due to the degradation of the fillers (Figure 10c) as well as the degradation of the interfaces between the matrix and the fillers. Figure 11a and 12a shows micrographs of the fracture surfaces of typical

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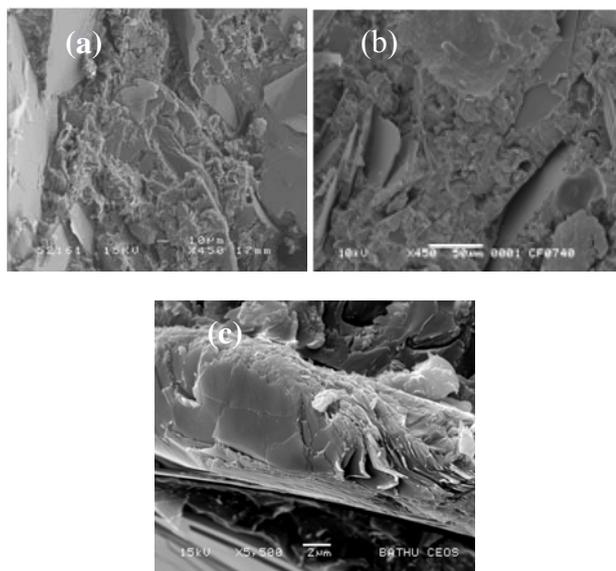non-exposed CB10TSS and Albipox samples respectively.

Figure 10: SEM micrographs of fracture surfaces of Timberset: (a) control, x450, (b) exposed to 50°C and 95% RH, x 450, and (c) showing the degradation of the fillers, x 5500.
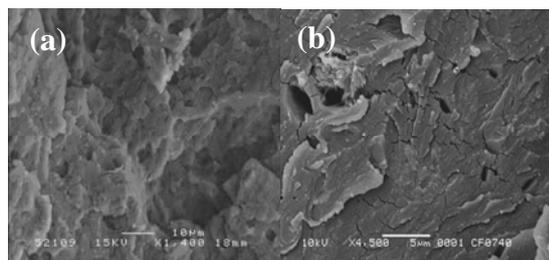

Figure 11: SEM micrographs of fracture surface of CB10TSS: (a) control, x1400 and (b) exposed at 50°C and 95% RH , x 4500.
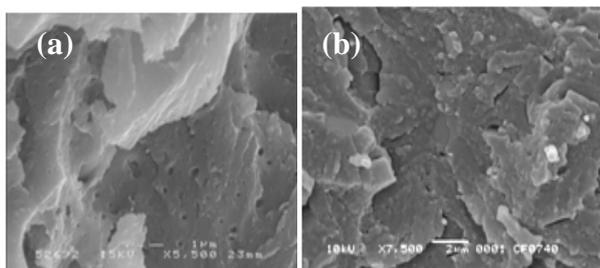

Figure 12: SEM micrographs of fracture surface of Albipox: (a) control, x5500 and (b) exposed at 50°C and 95% RH, x 7500.

Both fracture surfaces show homogenous and dense structures which suggests good interfacial adhesion. The aged CB10TSS (Figure 11b) has a flatter surface, with smoothing of the matrix and extensive cracking.

The other possible reason for this reduction may be material degradation such as hydrolysis or oxidation which can be observed from the changes in colour (dark to lighter brown).

The Albipox (Figure 12b) still retains some surface roughness but the little pores which indicate phase separation have diminished suggesting that the nano-rubber particles have recombined with the matrix. However these microscopical changes do not have a great effect on the strength and stiffness compared to CB10TSS.

3.2 Glass transition temperatures

The analyses of DSC thermograms are summarized and presented in Table 2. The Tg was determined from the midpoint value of the jump in heat flow.

Table 2: Summary of the glass transition temperature values determined from DSC tests for the three adhesives before and after exposure to 50°C95%RH.

Aging Conditions	Tg (°C)		
	CB10TSS	Albipox	Timberset
Control	39.5	51.5	53.6
50°C/ 95%RH	32.0	53.3	78.8

It can be seen that the addition of nano and micro particles have helped in improving the Tg in the order of Timberset > Albipox > CB10TSS. As the temperature of exposure increases from 20°C to 50°C, Table 2, Tg shifts towards higher temperatures except for CB10TSS. 50°C is higher than Tg for CB10TSS and the presence of humidity has further plasticized the adhesive which attributed to the reduction in Tg and also the reduction in tensile strength as seen in Section 3.1 above. In the case of Albipox and Timberset , the Tgs are higher than 50°C and the presence of nano and micro-filler addition may reduce the moisture uptake, hence improving the Tgs. Timberset shown to have the highest Tg because it has a denser and more rigid polymer (due to the heavily filled of ceramics particles) than Albipox and CB10TSS, therefore it possesses a higher density of cross-links resulting in a decrease in free space and causing less effect due to water uptake. However the tensile strength for Timberset reduced much more than Albipox which due to debonding of the fillers. Unlike Timberset, the presence of moisture and high temperature has caused the rubber particles to cavitate and stiffer the polymer chain, hence increase in Tg and the least reduction in strength. Cook and Tod [1993] suggest that Tg is depressed by the presence of moisture but as the temperature increases moisture is driven off and the adhesive samples cure further modifying the mechanical properties.

3.3 Block shear strength

Figure 13 shows the changes in shear strength in bonded timber with different adhesives with respect to aging times in 50°C and 95%RH. The results of shear strength of adhesive-timber joint are also presented in Table 3.
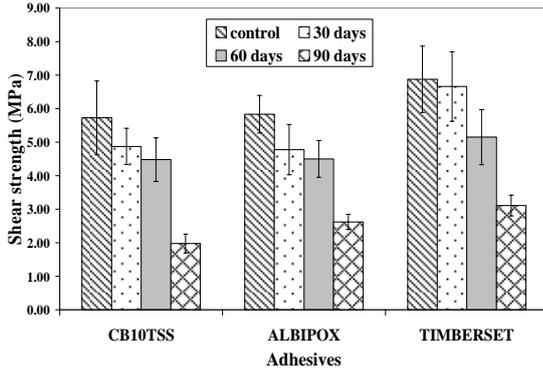
Figure 13: Shear strength from block shear test for different adhesives at different aging times in 50°C and 95% RH

Table 3: Shear strength of adhesive-timber joint after 90 days aging at 50°C/95%RH and standard block shear specimens held at 20°C/65%RH.

Aging Conditions	Adhesive	Shear strength		Failure mode (a,t,ta)*
		Mean (MPa)	COV (%)	
20°C/ 65%RH (Control)	CB10TSS	5.7	6.5	100% t
	Albipox	6.4	6.6	100% t
	Timberset	6.9	5.6	100% t
50°C /95%RH.	CB10TSS	2.0	14.0	100% t
	Albipox	3.0	5.0	100% t
	Timberset	3.1	10.0	100% t

* a - adhesive failure,
  ta-timber/adhesive failure,
  t – timber failure,

In dry state, Timberset developed 20% higher shear strength compared to CB10TSS and only 7% higher than Albipox. The high shear strength in Timberset may be due to high MOE of the filler added but the improved shear strength of Albipox (11.9% higher) compared to CB10TSS can be attributed to the improvement in the interfacial interaction of the rubber nanoparticle with the epoxy-based adhesive which provide better wetting.

After aging the shear strength of CB10TSS reduces by 65.4%, Albipox reduces by 52% and Timberset reduces by 55%. Even though Timberset still posses higher shear strength after 90 days but actually the strength has reduced much more compared to Albipox. (The lost in strength for the adhesives due to hot and wet environment has been explained in section 3.1). This indicates that timber joint with Albipox be able to endure the hot and wet environment better than the timber bonded with other resins. The high percentage of wood failure in the shear joints were further indicates that the adhesives are still stronger than the wood in hot and wet condition.

3.3 Pull-out strength

The failed pull-out test specimens showed three different failure modes as shown in Figure 14.
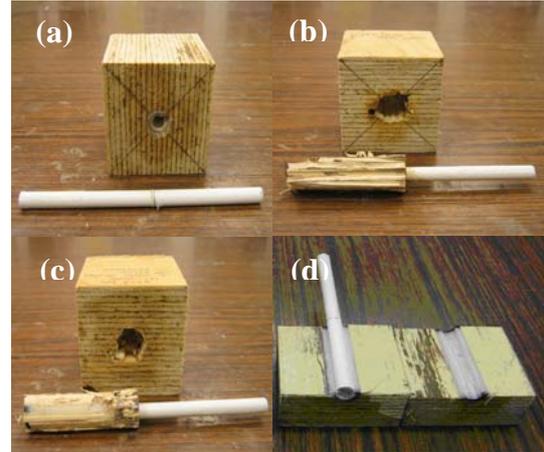

Figure 14: Different modes of failure; (a) rod/adhesive failure (ra), (b) timber failure (t), (c) timber/adhesive failure (ta) and (d) showing the hole has been filled with adhesives without cavity.

Based on the type of failure the average shear stress at the adhesive, timber and rod interfaces was calculated by dividing the failure load by the bond area using Equation (3) and (4):

Adhesive-timber interface

$$\tau_{ta} = \frac{P_{max}}{\pi \phi_{hole} L} \qquad (3)$$

and rod-adhesive interface

$$\tau_{ra} = \frac{P_{max}}{\pi \phi_{rod} L} \qquad (4)$$

where ϕ_{hole} and ϕ_{rod} are the diameters of the drilled hole and rod respectively and L is the rod embedment length which was 50mm in all cases.

Because of the different diameter, it can clearly be seen that the bond area at the adhesive/timber interfaces is bigger than the bond area at the adhesive/rod interface which will have significant factor on the strength.

Figure 15 and 16 details the shear strength for both at rod/adhesive and timber/adhesives interface as a function of aging time and the average shear strength shown indicate a trend. Table 4 shows the summary of the pull-out tests results. After long period of exposure to hot and wet environment, the shear strength decreases for all three adhesives. For CB10TSS and Albipox, after initial aging and water uptake, the structural integrity of the adhesive joint was surprisingly improved. The rise in the shear strength $_{ra}$ for CB10TSS and Albiox was recorded at 30 days to 21% and 27% respectively. This effect may be attributed to stress relaxation phenomenon within the GFRP rod region or wood region which result in the aging effectively strengthen the interface region.
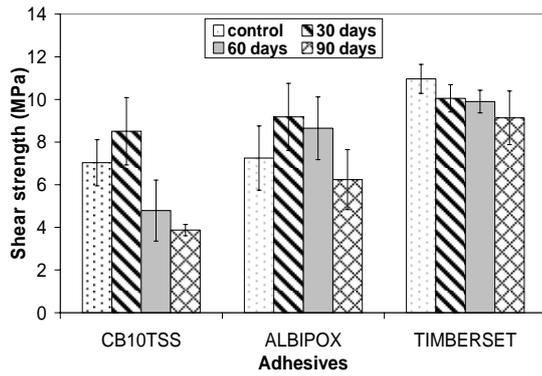
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Figure15: The shear strength at rod adhesive interface as a function of aging in 50°C and 95% RH
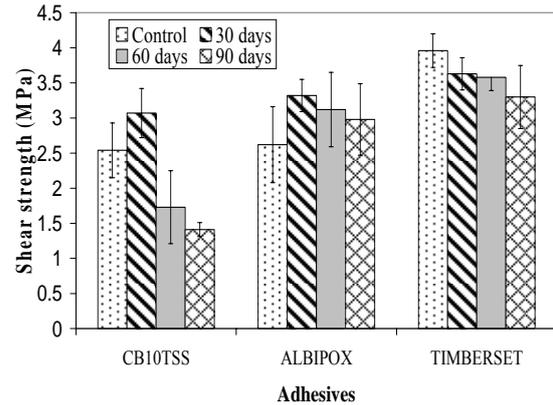

Figure16: The shear strength at timber adhesive interface as a function of aging in 50°C and 95% RH.

Table 4: Results of pull-out specimens tested after aging in 50°C and 95% RH

Days of aging	Adhesives	Pull-out strength		Shear stress at rod adhesive interface		Shear stress at timber adhesive interface		Failure Mode (ra, ta, t, rat)*
		P_{max} (kN)	S.D	τ (MPa)	S.D	τ (MPa)	S.D	
control	CB10TSS	11.12	1.62	7.03	1.08	2.54	0.39	100% ra
	Albipox	11.48	1.82	7.25	1.15	2.62	0.42	100% ra
	Timberset	17.35	1.07	10.96	0.68	3.96	0.24	40% ra, 40% t, 20% rat
30	CB10TSS	13.47	1.50	8.51	1.58	3.07	0.57	70% ra, 30% rat
	Albipox	14.53	1.38	9.18	1.50	3.32	0.54	100% ra
	Timberset	15.91	1.02	10.05	0.64	3.63	0.23	20% ta, 80% rat
60	CB10TSS	7.58	1.26	4.74	1.43	1.73	0.52	80% ra, 20% rat
	Albipox	13.69	1.33	8.45	1.47	3.12	0.53	100% ra
	Timberset	14.69	0.84	9.90	0.53	3.58	0.19	20% ra, 20% t, 60% rat
90	CB10TSS	6.16	0.42	3.89	0.27	1.41	0.10	100% ra
	Albipox	13.25	1.81	8.37	1.14	3.02	0.41	100% ra
	Timberset	13.86	1.93	8.76	1.22	3.16	0.44	100% ra

* ra - rod/adhesive failure, ta - timber/adhesive failure,
t – timber failure,   rat–rod/adhesive/timber failure

At 60 days onwards, the stress relaxation may have finished and at 90 days the joint strength for CB10TSS and Albipox lost 44.7% and 15.4% respectively of their initial strength. As for Timberset no rise in shear strength at 30 days but continued to fall and the shear strength has reduced by 20% after 90 days. This observation correlates well with observation made on the tensile strength of the adhesives due to aging in Section 3.1.

The difference in the shear strength values for these adhesives depends on chemical and mechanical bonding and is reflected in the failure modes. All shear failures occurred at the rod/ adhesives interface regardless of the type of adhesives used after 90 days aging however at 30 and 60 days they still exhibit adhesion failure at adhesives/timber interface.

This suggest that the failure of pull-out specimens was not controlled by the adhesives/timber interface strength but instead depended on the GFRP interface strength properties. This can be seen from the failure mode of control specimens where Timberset failed in three modes at the rod-adhesive interface (ra), in the timber (t) and in a combined rod-adhesive-timber mode (rat) while Albipox and CB10TSS failed mainly at the rod to adhesive interface which reflecting the strong interfacial bond between rod and Timberset. Ideally failure should occur in the wood rather than in the adhesive when the rod is used as a connector or reinforcement. When the

failure is mostly in the timber then the shear strength is higher. .Although the recommendations for surface preparation of the rods were followed [Harvey, 2000], further investigation is required to improve bonding between both CB10TSS and Albipox and the rod surface.

The LVL specimens bonded with Albipox adhesives and GFRP rods appeared to exhibit more settle reduction in pull-out strength with increasing aging time. Even in block shear specimens with Albipox also shows less reduction in strength compared to other adhesive

4. CONCLUSION

The following conclusions can be drawn from this study:

1. The addition of liquid rubber nano-fillers to epoxy based adhesives improves the tensile strength and glass transition temperature in dry and hot/wet environment.

2. The addition of liquid rubber nano-fillers had significant improvement in the performance on bond durability of timber and exhibited the least strength reduction in shear strength in both pull-out and block shear test after ageing in 50°C and 95% RH.

3. The addition of micro-fillers improves the Modulus of Elasticity and glass transition temperature of the epoxy based adhesives in dry and hot/wet environment and also exhibited higher bond strength after 90 days ageing.

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