

TECHNICAL PAPER

TIMBER BEAM REPAIR BASED ON POLYMER-CEMENTITIOUS BLENDS

Doi: <http://dx.doi.org/10.1590/1809-4430-Eng.Agric.v37n2p366-375/2017>

**ANDRÉ L. CHRISTOFORO^{1*}, TULIO H. PANZERA², VICTOR A. DE ARAUJO³,
JULIANO FIORELLI⁴, FRANCISCO A. R. LAHR⁵**

^{1*}Corresponding author. Universidade Federal de São Carlos (UFSCar)/ São Carlos - SP, Brasil.

E-mail: christofoal@yahoo.com.br

ABSTRACT: This study aims to manufacture and apply polymer-cementitious blends based on a combination of epoxy polymer and Ordinary Portland Cement (OPC) for timber beam repair. The material was used to repair timber beams of “Maçaranduba” (*Manilkara* sp.) and “Cedro doce” (*Cedrella* spp) wood species. A full factorial design was conducted to investigate the effect of cement particle content (0wt%, 30wt%, 40wt% and 50wt %), type of cement (ASTM-II and ASTM-III), and pigment addition (0wt% and 0.2wt%) on the physical and mechanical properties of the blend. The cement content factor affected all properties investigated. The highest elastic modulus was achieved by the blends produced with 50wt% of cement and 0.2wt% of pigment inclusion. This condition was used to repair the timber beams evaluated under four-point bending test. The insertion of the blends in timber beams achieved superior load levels to the unreinforced woods in both species, inferior load levels to the reference condition (without defects) in “Cedro doce”, and superior to the reference condition in “Maçaranduba”. These results were justified by the low density of “Cedro doce”, providing a better blend-wood interface adhesion.

KEYWORDS: Wood, bending, beams, composite section, connectors.

INTRODUCTION

Beams and columns are structural elements present in most of architectural designs, which are commonly made of timber in both rural and urban buildings. Wood is a renewable resource which has the most suitable properties depending of its application, despite of its lightness as material. ALMEIDA *et al.* (2014) have reported the wood strength-density ratio is up to four times higher than steel. As reported for other materials, constructions made with timber beams require appropriate utilization and maintenance (CHRISTOFORO *et al.*, 2013). Improper treatment can lead to problems which may compromise the purposes for which the wood beams were designed (FERREIRA *et al.*, 2014). Repairs or reinforcements of certain areas may be necessary to increase the structural support capacity, so that the whole structure remains intact. Other factors, such as design or construction errors, strength degradation, aging of materials and changes in design standards (stricter provisions or accidents) have motivated the development of new materials for repairing. Composites have been widely used to repair structural beams (MARQUES *et al.*, 2015), with immunity to corrosion, high strength and a simple application technique (aesthetics is not greatly affected).

Laminate composite materials made with natural (sisal, palm fibre, jute, etc.) and synthetic fibres (glass and carbon) have been used to reinforce timber beams, as indicated in the literature (LYONS & AHMED, 2005; BORRI *et al.*, 2005; CORRADI *et al.*, 2006; ALAM *et al.*, 2009; CAMPILHO *et al.*, 2009; JANKOWSKI *et al.*, 2010; MOHAMAD *et al.*, 2011; FIORELLI & DIAS, 2011; CARVALHO *et al.*, 2012; GARCÍA *et al.*, 2013; FERREIRA *et al.*, 2014; and, MIOTTO & DIAS, 2015), wherein reinforcement with laminated composites in timber elements provide good results.

² Universidade Federal de São João del-Rei (UFSJ)/ São João del-Rei - MG, Brasil.

³ Escola Superior de Agricultura "Luiz de Queiroz", Universidade de São Paulo (ESALQ/USP)/ Piracicaba - SP, Brasil.

⁴ Faculdade de Zootecnia e Engenharia de Alimentos, Universidade de São Paulo (FZEA/USP)/ Pirassununga - SP, Brasil.

⁵ Escola de Engenharia de São Carlos, Universidade de São Paulo (EESC/USP)/ São Carlos - SP, Brasil.

Received in: 6-24-2016

Accepted in: 10-17-2016

The use of particulate composites as reinforcement for timber beams has also been investigated in the literature. BRAZ *et al.* (2013) have reported the use of a polymer-ceramic blend (PANZERA *et al.*, 2010) to repair the compressive zone of timber beams. The finite element analysis (FEA) has pointed out the polymer-cementitious blend as an alternative solution for reinforcement of timber beams, presenting excellent strength and stiffness properties in compression.

Cementitious composites have been reinforced with synthetic and natural fibres. A thermoset polymer phase has also been added to enhance the mechanical properties of cementitious composites. PANZERA *et al.* (2010) have evaluated the effect of the epoxy polymer combined with the white Portland cement. The incorporation of 50wt% (weight fraction-wt%) of epoxy polymer into a Portland cement paste resulted in superior mechanical properties compared to the reference condition.

PANZERA *et al.* (2012) have also reported the effect of carbon nanotube (CNT) inclusions into polymer-cementitious composites. The CNTs must be treated to avoid the clustering effect, in which hinders the mechanical properties of the composites. Composites made with 25wt% of polymeric phase, without water and CNTs inclusions have exhibited superior mechanical strength. CNTs can be applied as a piezoresistive sensor being able to monitor the stress-strain field of civil structures.

Cement mortars have been prepared with steatite (soapstone) particles and epoxy polymer for restoration proposals. A higher compressive strength (43 MPa) and a lower porosity level (0.19%) have been achieved when steatite particles ranging from 0.42 mm to 1.41 mm and 40wt% of epoxy polymer have been added. This setup condition presented similar aesthetic features when compared to a natural soapstone surface (COTA *et al.*, 2012).

The reinforcement and restoration of timber beams has also been conducted by using laminated composites. A similar research has been carried out on the use of particulate composites and blends for timber repairing proposal. Based on the previous research performed by PANZERA *et al.* (2010), this study evaluates the physical and mechanical properties of a polymer-cementitious blend manufactured with epoxy polymer and Ordinary Portland Cement (OPC) in order to repair or to reinforce timber beams. A powder pigment was added to the mixture to attain similar aesthetic characteristics of wood beam surface. The effect of the pigment particles into the physical and mechanical properties of the manufactured material was also assessed in this study.

MATERIAL AND METHODS

Epoxy resin (Araldite-M) and hardener (HY 956) were supplied by Huntsman Company (Brazil). They were manually mixed based on a ratio of 1:0.4 (resin:hardener) ratio, and the manufactured blend were inserted into silicone moulds (compressive test) and drawn after 72 hours of curing time. The Ordinary Portland Cement (OPC-Type II and III) was supplied by Cauê Company (Brazil). Brown-coloured powder pigment was supplied by Xadrez Company (Brazil).

Compressive tests on the repairing material were carried out based on the American Standard D695-02 (ASTM, 1998) by the use of a universal testing machine Shimadzu AG-X Plus (100 KN load capacity) with a non-contacting video extensometer. Physical tests were conducted based on British Standard BS10545-3 (1997). Ten cylindrical specimens of 40mm in height and 20mm in diameter ($H/D = 2$) (ASTM, 1998) were fabricated for each experimental condition and replicate to perform the physical (five specimens) and the mechanical (five specimens) tests. Two replicates were considered in this experiment, with a total of 320 specimens.

Experimental factors (levels) investigated in this research were: OPC content (0wt%, 30wt%, 40wt% and 50wt%), OPC type (ASTM-II and ASTM-III), and pigment addition (0wt% and 0.2wt%). A full factorial design of $4^1 2^2$ was conducted to evaluate the effect of the factors on the following response variables: modulus of elasticity (E) and compressive strength (S), apparent density (ρ_a), bulk density (ρ_b), and apparent porosity (P), running the total of 16 experimental

conditions (Table 1). The bulk density was obtained via Archimedes principle following the recommendations of BS10545-3 (1997). The bulk density was calculated by the quotient of dry mass (m_1) divided by the external volume (V), including pores. The external volume (V) is determined subtracting the wet specimen mass (m_2) by the suspended wet specimen mass (m_3), both impregnated by immersion under vacuum. The apparent porosity, expressed as a percentage, is the relationship of the volume of the open pores of the test specimen to its exterior volume. The apparent porosity (P) is calculated using the equation:

$$P = \frac{m_2 - m_1}{V} \times 100$$

TABLE 1. Experimental conditions of the blend material.

EC	Pigment (wt%)	OPC (Type)	OPC (wt%)
1	0.2	ASTM-II	0
2	0.2	ASTM-II	30
3	0.2	ASTM-II	40
4	0.2	ASTM-II	50
5	0.2	ASTM-III	0
6	0.2	ASTM-III	30
7	0.2	ASTM-III	40
8	0.2	ASTM-III	50
9	0	ASTM-II	0
10	0	ASTM-II	30
11	0	ASTM-II	40
12	0	ASTM-II	50
13	0	ASTM-III	0
14	0	ASTM-III	30
15	0	ASTM-III	40
16	0	ASTM-III	50

Experimental conditions (EC); weight fraction (wt%); ordinary Portland cement (OPC); American Society for Testing and Materials standards II and III (ASTM).

The analysis of variance (ANOVA) at 5% of significance level (α) was applied to identify the main and interaction effects on the response-variables. Equivalence among mean values was assumed as a null hypothesis (H_0), and non-equivalence as an alternative hypothesis (H_1). P-values equal to or less than 0.05 imply rejection of H_0 , which reveals that the factor significantly affected the evaluated properties. ANOVA was evaluated with the support of Minitab® software, version 14.

ANOVA was validated by the Anderson-Darling test, which evaluates the normal distribution of the data, and Bartlett and Levene tests, which verify the homogeneity of variances between treatments. The Anderson-Darling test considers a normal distribution as null hypothesis and non-normality as alternative hypothesis. A P-value greater than the significance level of (0.05) implies to accept H_0 , rejecting it otherwise. Bartlett and Levene test considers the equivalence of variances among treatments as the null hypothesis, and non-equivalence as alternative hypothesis. P-value greater than the significance level of (0.05) implies to accept H_0 , rejecting it otherwise.

Timber beam dimensions were set at $1000 \times 45 \times 45 \text{ mm}^3$ (Figure 1), which were evaluated via four-point static bending test to analyse the behaviour of the reinforcing material. A cavity of $1 \text{ mm} \times 80 \text{ mm}$ was made in the middle of the timber beam (Figure 1b) to insert a structural defect. The best setup condition (Table 1) which results in the highest compressive modulus of elasticity was used to repair the timber beams (Figure 1c) of “Maçaranduba” (*Manilkara* sp) and “Cedro doce” (*Cedrella* spp) wood species.

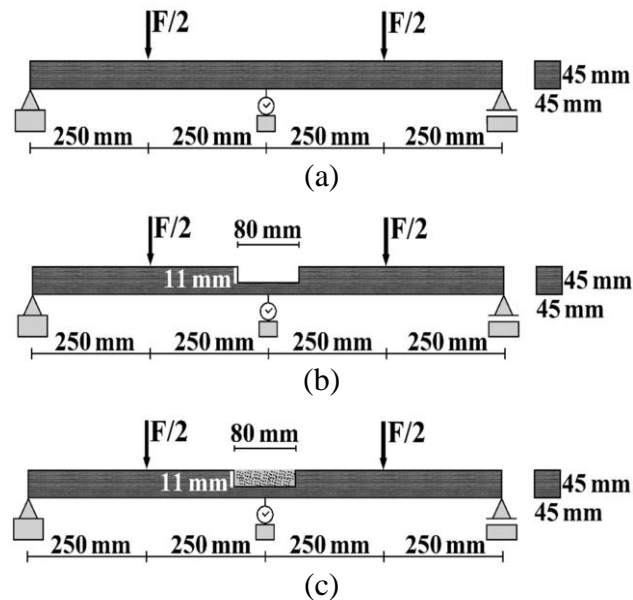


FIGURE 1. Experimental conditions for timber beams: reference-RC (a), with failure-WF (b) and repaired failure-RF (c).

Four-point bending tests were conducted in a non-destructive way, following the recommendations of the Brazilian Standard ABNT NBR 7190 (1997). The largest displacement value was limited to $L/200$ ratio (L is the support distance, $L=1000$ mm in Figure 1), in which ensured the serviceability limit state (SLS). The load was recorded when 5 mm of displacement was achieved. This methodology enabled to perform three consecutive tests in the same specimen for each experimental condition. Ten specimens per wood species with 12% moisture content were evaluated, running a total of 60 bending tests. The ANOVA was conducted to investigate the effect of the experimental conditions (RC, WF and RF) on the load values related to the limit displacement of 5 mm. After the load recording at $L/200$, the bending test was performed until failure in order to compare and evaluate the failure modes at reference (RC), with failure (WF) and repaired failure (RF) conditions (see Figure 1).

Besides the bending tests, six specimens for each wood species were manufactured to be evaluated in compressive tests. The modulus of elasticity (E_{c0}) and the compressive strength (f_{c0}) in a parallel direction to the grain were determined. Six specimens were also used to obtain the apparent density ($\rho_{12\%}$ - density obtained for moisture content of 12%) and porosity (P) following the prescriptions of the Brazilian standard (ABNT NBR 7190:1997). These properties were useful to better assess the results achieved for the static bending tests.

A micro structural analysis was conducted by scanning electron microscopy with energy dispersive spectroscopy (EDS) to verify the polymer-ceramic blends. Hitachi TM-3000 microscope was used in backscattered electron mode operating at 15 kV.

RESULTS AND DISCUSSION

Blend Evaluation

Table 2 indicates the physical and mechanical properties attained for the polymer-cementitious blends (C1-C16). It is also presented the variation coefficient (VC %) of the E , σ_f , ρ_B , ρ_A , and P ranged in the intervals [6%, 13%], [6%, 19%], [2%, 7%] [2%, 6 %], [5%, 15%] and [3%, 18%], respectively, which consider the lowest and highest values found for the 16 experimental conditions investigated.

TABLE 2. Physical and mechanical properties of the blends.

EC	E (MPa)	σ_f (MPa)	ρ_B (g/cm ³)	ρ_A (g/cm ³)	P (%)
C1	5198	75.82	0.22	1.25	1.70
C2	5611	70.94	0.25	1.42	2.85
C3	7347	78.64	0.28	1.63	2.68
C4	8584	71.72	0.30	1.70	3.13
C5	5095	76.25	0.22	1.25	1.70
C6	5487	73.99	0.27	1.48	2.71
C7	6318	74.38	0.26	1.57	2.97
C8	7860	65.59	0.25	1.56	2.20
C9	5336	74.73	0.20	1.18	4.05
C10	6747	73.99	0.26	1.50	3.07
C11	7190	79.55	0.29	1.59	2.65
C12	8003	75.62	0.30	1.72	2.65
C13	5337	74.73	0.20	1.18	4.05
C14	6391	75.49	0.26	1.43	2.78
C15	6707	77.48	0.28	1.59	2.30
C16	8293	72.27	0.27	1.60	2.49

Experimental conditions (EC); modulus of elasticity (E); compressive strength (σ_f), bulk density (ρ_B) apparent density (ρ_A); apparent porosity (P).

Table 3 shows the results for normal distribution (Anderson-Darling), homogeneity of variances (Barlett and Levene) and ANOVA (159 degrees of freedom) for the mechanical and physical properties. The nomenclatures such as, Pig, T, and %C represent the mains factors pigment, type of cement, and cement content, respectively; and Pig×T, Pig×%C, T×%C and Pig×T×%C represent the interactions between factors. The P-values obtained from the Anderson-Darling, Barlett and Levene tests (Table 3) were higher than 0.05 (confidence level), being in accordance to the normality and homogeneity conditions, consequently validating the ANOVA model.

TABLE 3. Anderson-Darling, Barlett, Levene, and ANOVA Results.

Responses	P-value ≥ 0.05			ANOVA (P-value ≤ 0.05)		
	Anderson-Darling	Bartlett	Levene	Pig	T	%C
E	0.412	0.283	0.493	0.254	0.146	0.000
σ_f	0.239	0.164	0.270	0.000	0.000	0.000
ρ_B	0.591	0.331	0.419	0.972	0.000	0.000
ρ_A	0.476	0.368	0.526	0.491	0.308	0.000
P	0.799	0.458	0.603	0.000	0.083	0.006
Responses	P-value (ANOVA)					
	Pig×T	Pig×%C	T×%C	Pig×T×%C		
E	0.000	0.000	0.000	0.000		
σ_f	0.061	0.000	0.000	0.003		
ρ_B	0.570	0.000	0.000	0.173		
ρ_A	0.002	0.000	0.000	0.000		
P	0.974	0.000	0.083	0.028		

Modulus of elasticity (E); compressive strength (σ_f), bulk density (ρ_B) apparent density (ρ_A); apparent porosity (P); pigment (Pig); type of cement (T); cement content (%C); factor interactions (Pig×T, Pig×%C, T×%C, Pig×T×%C).

The factor “OPC content” significantly affected all properties (Table 3), but the same did not occur for the “cement type and pigment incorporation”. A third order interaction effect was evident ($P \leq 0.05$) for all responses, except for bulk density. Table 4 shows the Tukey test for those significant factors revealed by the ANOVA. Tukey test indicates whether the experimental levels are significantly different. The treatment with the largest mean value is indicated by the letter A, the

treatment with the second largest mean value by the letter B, and so on; thus identical letters for different treatments indicate the statistical equivalence between means.

The compressive modulus of elasticity (MOE) was affected only by the OPC content (Tab. 4), presenting the best result when the blend was made with 50wt% of cement. All main factors were significant for the compressive strength response. The powder pigment reduced the strength of the blends, since these particles cannot be considered a reinforcing phase; the OPC type II showed better results when compared to Brazilian cement ASTM-III; and 50wt% of cement content provided the best compressive strength.

TABLE 4. Tukey test for the physical and mechanical properties of the blends.

Modulus of elasticity (E)								
Grouping	Pig (wt%)		OPC (Type)		OPC (wt%)			
	0.2%	0%	ASTM-II	ASTM-III	0%	30%	40%	50%
	A	A	A	A	D	C	B	A
Compressive strength (S)								
Grouping	Pig (wt%)		OPC (Type)		OPC (wt%)			
	0.2%	0%	ASTM-II	ASTM-III	0%	30%	40%	50%
	B	A	A	B	B	C	D	A
Bulk density (ρ_B)								
Grouping	Pig (wt%)		OPC (Type)		OPC (wt%)			
	0.2%	0%	ASTM-II	ASTM-III	0%	30%	40%	50%
	A	A	A	B	C	B	A	A
Apparent density (ρ_A)								
Grouping	Pig (wt%)		OPC (Type)		OPC (wt%)			
	0.2%	0%	ASTM-II	ASTM-III	0%	30%	40%	50%
	A	A	A	A	D	C	B	A
Apparent porosity (P)								
Grouping	Pig (wt%)		OPC (Type)		OPC (wt%)			
	0.2%	0%	ASTM-II	ASTM-III	0%	30%	40%	50%
	B	A	A	A	B	AB	A	A

Weight fraction (wt%); ordinary Portland cement (OPC); American Society for Testing and Materials standards II and III (ASTM); modulus of elasticity (E); compressive strength (σ_c), bulk density (ρ_B) apparent density (ρ_A); apparent porosity (P); pigment (Pig); type of cement (T); cement content (%C).

The pigment incorporation did not affect the bulk and apparent densities. The OPC ASTM-III provided better results for the bulk density (lower mean value), and the progressive cement content led to increased apparent and bulk densities of the blends.

Figure 2 shows the images obtained via scanning electron microscope (SEM) for the polymer-ceramic blends prepared with 50wt% of OPC ASTM-III without pigment (Figure 2a) and with pigment (Figure 2b). A dark grey scale is more evident for the blend made with pigment inclusion (Figure 2b), which reveals a denser cementitious material as reported by DIAMOND (2004). This behaviour is in accordance to the porosity results which reveals larger porosity levels for the blend without pigment (Table 2). On the other hand, the blends without pigment achieved higher compressive strength. This behaviour indicates that the pigment particles act as fillers, reducing the porosity; however, the physical adhesions between phases were not enough to enhance the mechanical strength of the blends.

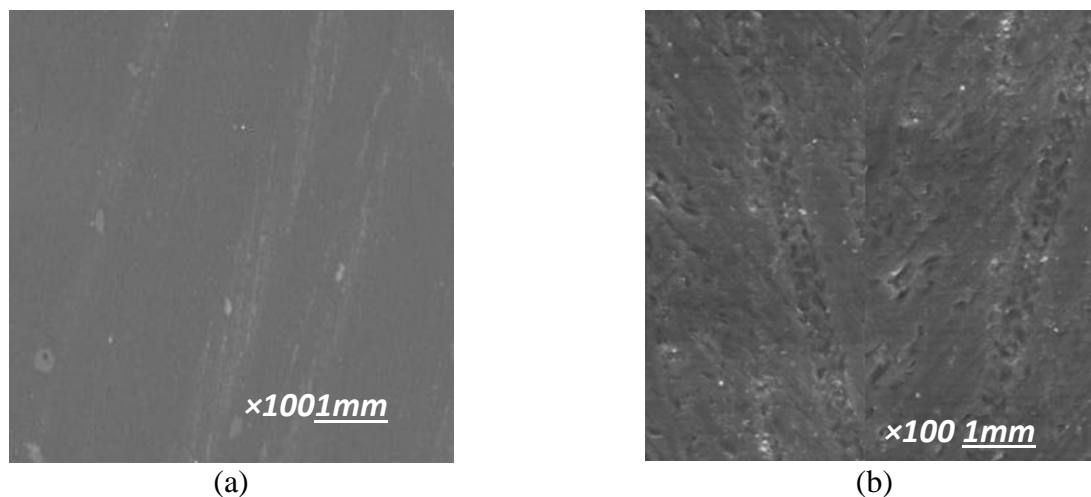


FIGURE 2. Polymer-cementitious blends: (a) without pigment-C16 and (b) with 0.2% of pigment-C8.

Tukey test showed that the best setup material used to repair damaged timber beams was the experimental condition C4 (Table 4), made with 0.2wt% of pigment and 50wt% of ASTM-II OPC, considering that the use of the pigment did not cause significant changes in the blend stiffness values.

Timber Repair Evaluation

Table 5 shows the load values obtained via bending test for both wood species, with sample mean (\bar{x}), variation coefficient (VC) and Tukey test results (grouping). Table 6 presents the sample mean and the variation coefficients of the physical ($\rho_{12\%}$) and mechanical properties (E_{c0} ; f_{c0}) obtained for both wood species.

TABLE 5. Load results (FL/200) obtained via bending tests.

	“Maçaranduba” – FL/200		
	RC	WF	RF
\bar{x} (kN)	13.55	9.15	11.86
VC (%)	18	19	17
Grouping	A	C	B
	“Cedro doce” – FL/200		
	RC	WF	RF
\bar{x} (kN)	6.43	4.32	6.17
VC (%)	21	23	23
Grouping	A	B	A

Reference condition (RC); condition with failure (WF); repaired failure condition (RF); variation coefficient (VC); sample mean (\bar{x}).

TABLE 6. Physical and mechanical properties obtained for the wood species.

Maçaranduba	Stat.	f_{c0} (MPa)	E_{c0} (MPa)	$\rho_{12\%}$ (kg/m ³)
	\bar{x}	106.32	23546	1228
	VC (%)	15.34	13.21	2.26
Cedro doce	Stat.	f_{c0} (MPa)	E_{c0} (MPa)	$\rho_{12\%}$ (kg/m ³)
	\bar{x}	28.76	7623	473
	VC (%)	18.51	16.22	3.45

- variation coefficient (VC); sample mean (\bar{x}); modulus of elasticity (E_{c0}); compressive strength (f_{c0}); apparent density at 12% of moisture content ($\rho_{12\%}$).

Table 6 shows that the mean apparent density for “Maçaranduba” wood was 2.60 times higher than the apparent density for “Cedro doce” and 3 and 3.70 times higher than the compressive modulus and strength data, respectively.

P-values lower than 0.05 presented by RC and RF factors indicate the repair effect was significant. P-values reached for *Maçaranduba* wood load response were superior to 0.05 for both Anderson-Darling (0.275) and Bartlett (0.538) tests. For *Cedro doce* wood, P-values of 0.153 and 0.349 corresponds to the normality and homogeneity testing, respectively, which validates the ANOVA model. Tukey test (Table 5) indicated that the blend was not able to recover the load capacity of “*Maçaranduba*” timber beam; however, only 12% reduction on the load value (FL/200) was achieved when compared to the reference condition. Furthermore, blend repairing led to 30% increasing in load capacity over the beams in reference condition (RC) and without reinforcement (WF), indicating an enhancement effect. Tukey test (Table 5) revealed that the polymer cementitious blend was able to recover beam load capacity for “*Cedro doce*” wood. This material provided an appropriate characteristic for wood beams repair, as pointed out by BRAZ *et al.* (2013), and this fact can be attributed to the lower density of “*Cedro doce*” wood, allowing a major penetration of the epoxy polymer as compared to “*Maçaranduba*” wood species. Figure 3 shows the rupture modes obtained for “*Maçaranduba*” and “*Cedro doce*” wood specimens after four-point bending test. The rupture of the pieces presented the same profile behaviour, in which the crack was initiated by tension at the bottom side of the beam, and subsequently it was propagated at the blend-wood interface with no damage across the blend and no delamination process, revealing a promising material for such application.

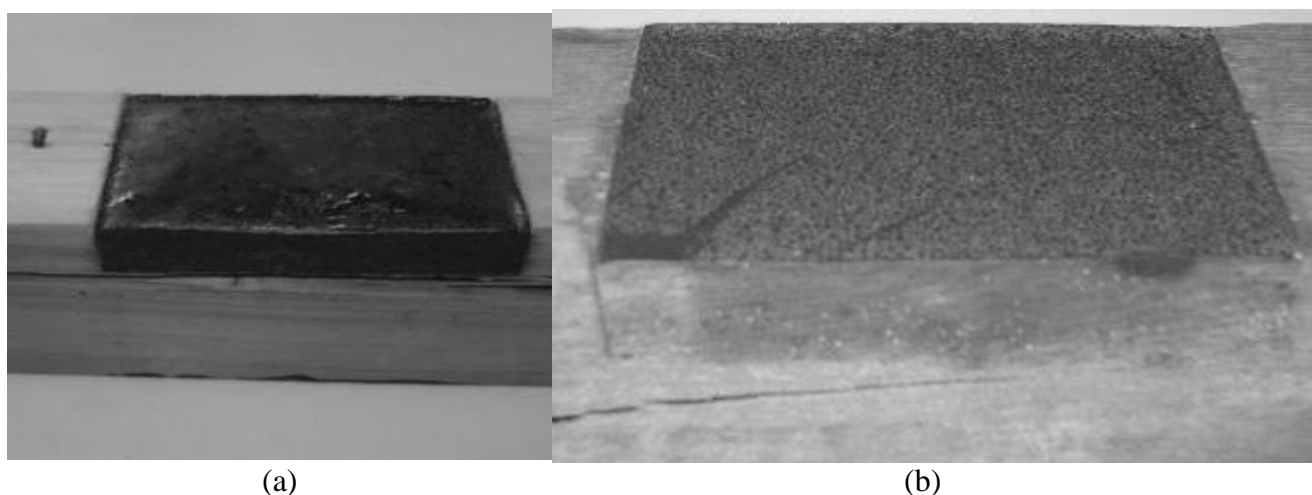


FIGURE 3. Rupture modes with the blend: (a) “*Maçaranduba*” and (b) “*Cedro doce*”.

CONCLUSIONS

The main conclusions of this study are following described:

- In general, the pigment inclusion and the cement type revealed different behaviours on the investigated mechanical and physical properties. The cement content factor significantly affected all the response variables.
- The highest modulus of elasticity in compression was achieved when the polymer-cementitious blend was made with 50% of cement (ASTM-II) and 0.2wt% of powder pigment (C4). This setup was used to repair the timber beams under bending test.
- The repaired “*Maçaranduba*” timber beam provided superior values of load (FL/200) when compared to those of reference conditions. Once more, the efficiency of the wood repair was revealed being considered acceptable.
- Lower load values were achieved for “*Maçaranduba*” wood species when compared to the reference condition, being attributed to its higher compressive modulus when compared to the blend and its higher density (lower porosity), which hinders the physical adhesion at the wood-polymer interface.

- The repair of “Cedro doce” wood by C4 blend presented similar strength values compared to the reference condition. This behaviour can be attributed to the higher compressive modulus of the blend in comparison to “Cedro doce” wood. A lower density of “Cedro doce” specie might contribute to enhance the polymer-wood adhesion.
- The repair of both beam species by the use of the polymer-cementitious blend was considered appropriated under four-point bending test. The crack was initiated at the bottom beam side where high tensile loadings are reached, and subsequently the fracture was propagated toward the blend-wood interface due to the shear stress in the parallel direction to the grain of the wood.

REFERENCES

- ABNT - ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. NBR 7190. **Projeto de estruturas de madeira**. Rio de Janeiro: ABNT, 1997.
- ALAM, P.; ANSELL, M. P.; SMEDLEY, D. Mechanical repair of timber beams fractured in flexure using bonded-in reinforcements. **Composites Part B: Engineering**, Oxford, v. 40, p. 95-106, 2009.
- ALMEIDA, D. H.; CAVALHEIRO, R. S.; FERRO, F. S.; ALMEIDA, T. H.; CHRISTOFORO, A. L.; CALIL JR, C.; LAHR, F. A. R. Hardness of the *Schizolobium amazonicum* wood. **Advanced Materials Research**, Zurich, v. 912-914, p. 2018-2021, 2014.
- ASTM - AMERICAN SOCIETY FOR TESTING MATERIALS. D 695-02. **Compressive properties of rigid plastics**. West Conshohocken: ASTM, 1998.
- BORRI, A.; CORRADI, M.; GRAZINI, A. A method for flexural reinforcement of old wood beams with CFRP materials. **Composites Part B: Engineering**, Oxford, v. 36, p. 143-153, 2005.
- BRAZ, J. C. F.; LAYBER, R. B.; LAURO, C. H.; CHRISTOFORO, A. L.; PANZERA, T. H.; LAHR, F. A. R.; SILVA, V. R. V. Numerical evaluation of the mechanical behavior of a particulate composite material as reinforcement in timber beams. **International Journal of Composite Materials**, Rosemead, v. 3, p. 83-91, 2013.
- BSI - BRITISH STANDARDS INSTITUTE. EN ISO 10545-3. Ceramic tiles - Part III. **Determination of water absorption, apparent porosity, apparent relative density and bulk density**. London: BSI, 1997.
- CAMPILHO, R. D. S. G.; MOURA, M. F. S. F.; BARRETO, A. M. J. P.; MORAIS, J. J. L.; DOMINGUES, J. J. M. S. Fracture behaviour of damaged wood beams repaired with an adhesively-bonded composite patch. **Composites Part A: Applied Science and Manufacturing**, Oxford, v. 40, p. 852-859, 2009.
- CARVALHO, S. S.; DUTRA, J. R.; CARVALHO, A. L. C.; VIEIRA, L. M. G.; CHRISTOFORO, A. L. Experimental evaluation of the employment of a laminated composite material with sisal fibres as reinforcement in timber beams. **International Journal of Composite Materials**, Rosemead, v. 2, p. 97-100, 2012.
- CHRISTOFORO, A. L.; BLECHA, K. A.; CARVALHO, A. L. C.; RESENDE, L. F. S.; LAHR, F. A. R. Characterization of tropical wood species for use in civil constructions. **Journal of Civil Engineering Research**, Rosemead, v. 3, p. 98-103, 2013.
- CORRADI, M.; SPERANZINI, E.; BORRI, A.; VIGNOLI, A. In-plane shear reinforcement of wood beam floors with FRP. **Composites Part B: Engineering**, v. 37, p. 310-319, 2006.
- COTA, F. P.; ALVES, R. A. A.; PANZERA, T. H.; STRECKER, K.; CHRISTOFORO, A. L.; BORGES, P. H. R. Physical properties and microstructure of ceramic-polymer composites for restoration works. **Materials Science and Engineering: A**, Lausanne, v. 531, p. 28-34, 2012.
- DIAMOND, S. The microstructure of cement paste and concrete – a visual primer. **Cement and Concrete Composites**, Barking, v. 26, p. 919-933, 2004.

- FERREIRA, M. B.; CORREA, G. F.; PANZERA, T. H.; FIORELLI, J.; SILVA, V. R. V.; LAHR, F. A. R.; CHRISTOFORO, A. L. Numerical and experimental evaluation of the use of a glass fiber laminated composite materials as reinforcement in timber beams. **International Journal of Composite Materials**, Rosemead, v. 4, p. 73-82, 2014.
- FIORELLI, J.; DIAS, A. A. Glulam beams reinforced with FRP externally-bonded: theoretical and experimental evaluation. **Materials and Structures**, London, v. 44, p. 1431-1440, 2011.
- GARCÍA, P. R.; ESCAMILA, A. C.; GARCÍA, N. G. Bending reinforcement of timber beams with composite carbon fiber and basalt fiber materials. **Composites Part B: Engineering**, Oxford, v. 55, p. 528-536, 2013.
- JANKOWSKI, L. J.; JASIEŃKO, J.; NOWAK, T. P. Experimental assessment of CFRP reinforced wooden beams by four point bending testes and photo elastic coating technique. **Materials and Structures**, London, v. 43, p. 141-150, 2010.
- LYONS, J. S.; AHMED, M. R. Factors affecting the bond between polymer composites and wood. **Journal of Reinforced Plastics & Composites**, Westport, v. 24, p. 404-405, 2005.
- MARQUES, F. A. Z.; SILVA, C. E. G.; CHRISTOFORO, A. L.; LAHR, F. A. R.; PANZERA, T. H.; CANTO, R. B. Influence of Portland cement addition in the physical and mechanical properties of epoxy resin. **Advanced Materials Research**, Zurich, v. 1088, p. 411-414, 2015.
- MIOTTO, J. L.; DIAS, A. A. Structural efficiency of full-scale timber-concrete composite beams strengthened with fiberglass reinforced polymer. **Composite Structures**, Barking, v. 128, p. 145-154, 2015.
- MOHAMAD, G.; ACCORDI, J.; ROCA, L. E. Avaliação da associação de compósito de fibra de vidro e carbono no reforço de madeira de Eucalyptus in natura e autoclavada. **Matéria**, Rio de Janeiro, v. 16, p. 621-637, 2011.
- PANZERA, T. H.; SABARIZ, A. L. R.; STRECKER, K.; BORGES, P. H. R.; WASCONCELOS, D. C. L.; VASCONCELOS, W. L. Propriedades mecânicas de materiais compósitos à base de cimento Portland e resina epóxi. **Cerâmica**, São Paulo, v. 56, p. 77-82, 2010.
- PANZERA, T. H.; COTA, F. P.; SCHIAVON, M. A.; BOWEN, C.; CHRISTOFORO, A. L.; BORGES, P. H. R.; SCARPA, F. Full factorial design analysis of carbon nanotube polymer-cement composites. **Materials Research**, Warrendale, v. 15, p. 30-35, 2012.