3
Bond characteristics of treated bamboo strips embedded in concrete

3.1. Introduction

In contrast to steel, there is as yet no standardisation for the surface characteristics and bond test of bamboo strip reinforcement. Therefore, determining the bond characteristics of bamboo strips is a fundamental requirement for their practical use in concrete, as this influences the mechanism of load transfer characteristics between reinforcement and concrete. The use of bamboo as concrete reinforcement has been investigated for many authors [9-30], but only few [31-34] have studied mechanics to improve of bond stress transfer between bamboo reinforcement and concrete. Lima et al [14] reported that bond strength of natural (untreated) bamboo with concrete as 1.53 MPa (concrete compression strength 35MPa). Other authors have investigated treatments that could improve bond strength by adding to the surface of the bamboo asphalt emulsion, coal tar, dilute varnish and water-glass (sodium silicate) [32]. Waterproofing treatments have generally been the most widely studied.

Culzoni [31] treated the bamboo surface with a mixture of asphalt emulsion and sand as well as wrapping the bamboo strips with building wire, reaching 2.08 MPa bond stress. Acha (2002) [35] studied the use of bamboo as permanent shutter and reinforcement of concrete slabs applied on the bamboo surface a commercial epoxy resin before casting, improving the bond stress to 2.75 MPa.

In this chapter, based on results of bamboo surface treatments using epoxy resin [35], bamboo strips were fabricated for reinforced concrete. To enhance surface bonding on the bamboo (*Phyllostachys Pubescens*), two sizes of small gravel were bonded to the bamboo surface using polyester resin or epoxy resin. Eight different combinations of resin type, gravel size (2 or 4 mm) and procedures for cleaning the surface of the bamboo were developed. The efficiency of bond between bamboo and concrete was assessed by direct push-out tests. Results on bamboo surface treatments, test procedures and bond-slip curves results are presented and analysed.

3.2. Experimental program

3.2.1. Materials

Bamboo strips made from three to four year old Chinese *Phyllostachys Pubescens* was used, which had previously been gas fumigated against insect pests. The surface treatments and characteristics of the strips used are shown in Figure 3.1 and detailed in Table 3.1. The strip surface treatment, their geometrical and mechanical properties and the cross-section area (measured in the laboratory) are summarised in Table 3.1.

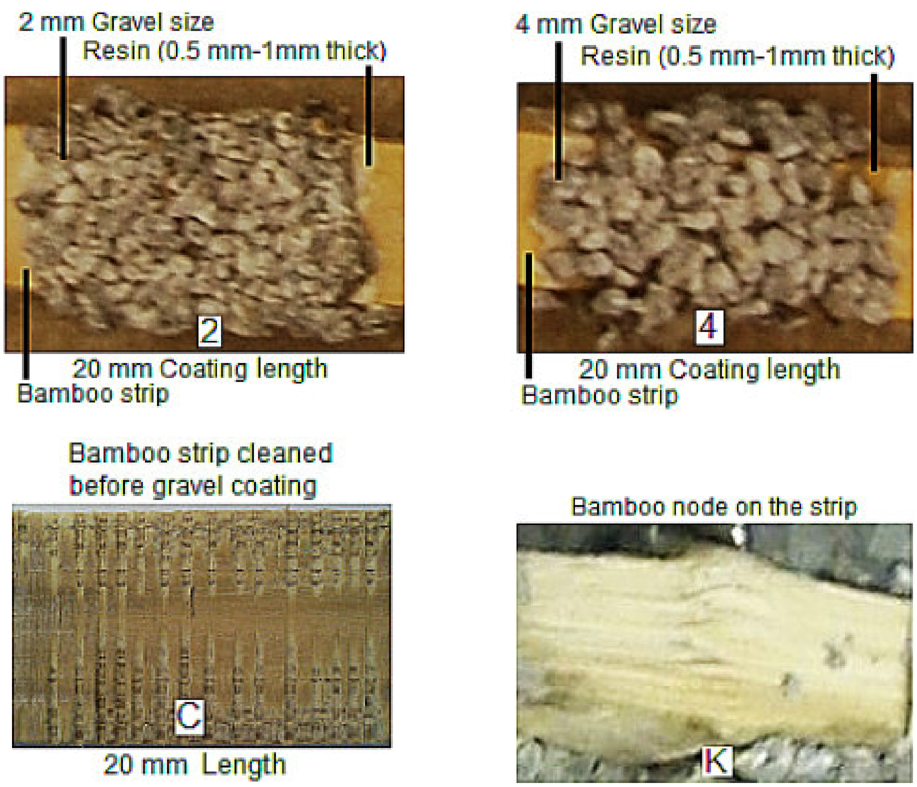


Figure 3.1- Bamboo strips surface treatments

Table 3.1- Surface treatment, Geometrical and mechanical properties of bamboo strips

Group	Surface treatment (l_c= 20mm length)				Cross section geometry				Mechanical properties	
	Gravel size(mm)	Resin	Node present	Surface Cleaned	p_i = Inner perimeter (mm)	p_e = External perimeter (mm)	T = Thick (mm)	Area (mm^2)	Comp. strength (MPa)	Comp. Elastic modulus (MPa)
2-E/N-N-1	2	Epoxy	No	No	21.1	25.1	8.0	185	51.3	5000
2-E/N-N-2	2	Epoxy	No	No	21.1	25.1	8.0	185	51.3	5000

2-E/N-N-3	2	Epoxy	No	No	18.6	22.6	8.0	165	53.5	5700
2-E/N-N-4	2	Epoxy	No	No	18.6	22.6	8.0	165	53.5	5700
2-E/K-C-1	2	Epoxy	Yes	Yes	21.1	25.1	8.0	185	51.3	5000
2-E/K-C-2	2	Epoxy	Yes	Yes	21.1	25.1	8.0	185	51.3	5000
2-E/K-C-3	2	Epoxy	Yes	Yes	18.6	22.6	8.0	165	53.5	5700
2-E/K-C-4	2	Epoxy	Yes	Yes	18.6	22.6	8.0	165	53.5	5700
4-E/N-C-1	4	Epoxy	No	Yes	21.1	25.1	8.0	185	51.3	5000
4-E/N-C-2	4	Epoxy	No	Yes	21.1	25.1	8.0	185	51.3	5000
4-E/N-C-3	4	Epoxy	No	Yes	18.6	22.6	8.0	165	53.5	5700
4-E/N-C-4	4	Epoxy	No	Yes	18.6	22.6	8.0	165	53.5	5700
2-E/N-C-1	2	Epoxy	No	Yes	21.1	25.1	8.0	185	51.3	5000
2-E/N-C-2	2	Epoxy	No	Yes	21.1	25.1	8.0	185	51.3	5000
2-E/N-C-3	2	Epoxy	No	Yes	18.6	22.6	8.0	165	53.5	5700
2-E/N-C-4	2	Epoxy	No	Yes	18.6	22.6	8.0	165	53.5	5700
2-P/N-N-1	2	Polyester	No	No	21.1	25.1	8.0	185	51.3	5000
2-P/N-N-2	2	Polyester	No	No	21.1	25.1	8.0	185	51.3	5000
2-P/N-N-3	2	Polyester	No	No	18.6	22.6	8.0	165	53.5	5700
2-P/N-N-4	2	Polyester	No	No	18.6	22.6	8.0	165	53.5	5700
2-P/N-C-1	2	Polyester	No	Yes	21.1	25.1	8.0	185	51.3	5000
2-P/N-C-2	2	Polyester	No	Yes	21.1	25.1	8.0	185	51.3	5000
2-P/N-C-3	2	Polyester	No	Yes	18.6	22.6	8.0	165	53.5	5700
2-P/N-C-4	2	Polyester	No	Yes	18.6	22.6	8.0	165	53.5	5700
4-P/N-C-1	4	Polyester	No	Yes	21.1	25.1	8.0	185	51.3	5000
4-P/N-C-2	4	Polyester	No	Yes	21.1	25.1	8.0	185	51.3	5000
4-P/N-C-3	4	Polyester	No	Yes	18.6	22.6	8.0	165	53.5	5700
4-P/N-C-4	4	Polyester	No	Yes	18.6	22.6	8.0	165	53.5	5700
2-P/K-C-1	2	Polyester	Yes	Yes	21.1	25.1	8.0	185	51.3	5000
2-P/K-C-2	2	Polyester	Yes	Yes	21.1	25.1	8.0	185	51.3	5000
2-P/K-C-3	2	Polyester	Yes	Yes	18.6	22.6	8.0	165	53.5	5700
2-P/K-C-4	2	Polyester	Yes	Yes	18.6	22.6	8.0	165	53.5	5700

The bamboo surface coating was prepared in the laboratory by painting the bamboo strips with epoxy or polyester resin (0.5mm-1mm in thickness) and then embedding the 2mm or 4mm aggregate pieces. After the resin was completely dry (after around five hours) the concrete specimens used for the push-out were cast. The concrete mix is given in Table 3.2. The mean concrete compressive strength was determined by testing five 100 mm cubes. The mean concrete strengths value is presented in Table 3.3.

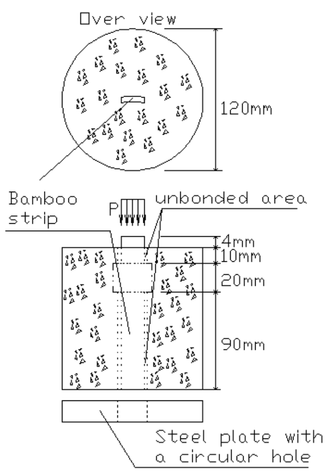
Table 3.2- Concrete mix

Water (kg/m^3)	195
Cement CEM II/B-V 32.5R (kg/m^3)	323
Fine aggregate (kg/m^3)	874
100mm Aggregate (kg/m^3)	877

3.2.2. Specimens, setup and testing equipment

To avoid crushing the bamboo fibres with the grips during tensile testing push-out bond testing was adopted instead. The bond strip cross-section and longitudinal coating length were defined according to the maximum compression strength of the bamboo (see Table 3.1). A 120 mm diameter and 120 mm high cylinder was used to manufacture the push-out specimens. The embedment length of the bamboo strips was limited to 20mm. To prevent bonding elsewhere and avoid end effects the bamboo strip surfaces were coated with grease (see Figure 3.2a). The concrete was poured with the bamboo strips centred in position inside the mould. After casting the specimens were transferred to a curing room for 24 hours. Thereafter, the concrete cylinders were de-moulded, marked and transferred again to the curing room at a temperature of 20 ± 2 ℃ and a relative humidity of 65%.

a)



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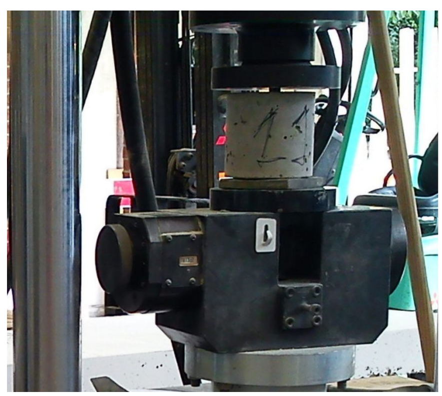


Figure 3.2- (a) Specimen’s dimensions (b) Push-out test set up

The push-out test setup is shown in Figure 3.2b. The tests were performed using a Dartec-hydraulic testing machine with a capacity of 100 kN. Displacement control was selected to capture the slip behaviour. The load was applied to the reinforcement strip at a rate of 0.5 mm/min and measured with the electronic load cell of the testing machine. An automatic data acquisition computer system was used to record the experimental output. The push-out specimen identification is defined in Figure 3.3. Four specimens for each configuration were tested. In total, 32 specimens were tested.

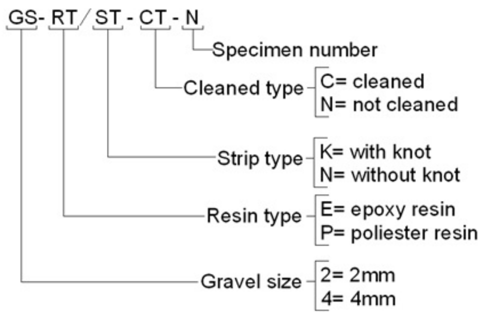


Figure 3.3- Specimen identification description

3.3. Experimental results

The influence of the gravel size, bonding resin type, type of surface cleaning and presence of a bamboo node on the bond behaviour is discussed in this section.

3.3.1. Bond strength

In the push-out test, the stress distribution is not constant along the embedment length. Hence, an average bond stress has been taken as:

$$\tau = \frac{P}{(2t + p_e + p_i) \times l_c} \qquad (3.1)$$

Where P is the compression load, t is the strip thickness, p_e is the external perimeter, p_i is the inner perimeter and l_c is the embedment length. The relationship between the bond stress defined by Eq. (3.1) and the slip between the bamboo strip and the resin is used to analyse the bond behaviour.

The experimental results obtained from the push-out tests, as well as the mode of failure, are given in Table 3.3. In Table 3.3: f'_c is the concrete compressive strength of the control cube specimens taken from all batches; τ_{max} is the bond strength; and s is the slip values at the bond strength for the loaded end. The mean values of the bond strength and the corresponding slips of nominally identical specimens are also reported. A normalised bond strength (τ^*_{max}), that accounts for the effect of the concrete strength, is defined by:

$$\tau^*_{max} = \frac{\tau_{max}}{\sqrt{f'_c}} \tag{3.2}$$

Table 3.3- Experimental results

Specimen[a]	P_{max} (kN)	τ_{max} (MPa)	$\tau_{max}{}^{b}$(MPa)	$\underline{s}$ (mm)	$\underline{s}^{b}$ (mm)	f'_c (MPa)	τ^*_{max} ($MPa^{0.5}$)	Failure mode[c]
2-E/K-C-1	8.83	7.10	7.19	2.020	2.013	32.8	1.24	P ;PO
2-E/K-C-2	8.84	7.10		1.834		32.8	1.24	P ;PO
2-E/K-C-3	8.34	7.29		1.992		32.8	1.27	P ;PO
2-E/K-C-4	8.31	7.27		2.204		32.8	1.27	P ;PO
2-E/N-C-1	7.93	6.37	6.66	1.969	2.011	32.8	1.11	P
2-E/N-C-2	8.43	6.77		1.946		32.8	1.18	P
2-E/N-C-3	7.55	6.60		1.946		32.8	1.15	P
2-E/N-C-4	7.91	6.91		2.184		32.8	1.21	P
2-E/N-N-1	5.96	4.79	4.64	0.955	0.905	32.8	0.84	P
2-E/N-N-2	6.19	4.98		0.953		32.8	0.87	P
2-E/N-N-3	5.55	4.86		0.810		32.8	0.85	P
2-E/N-N-4	4.52	3.95		0.900		32.8	0.69	P
4-E/N-C-1	6.86	5.51	5.38	1.255	1.238	32.8	0.96	P
4-E/N-C-2	6.52	5.24		1.286		32.8	0.92	P
4-E/N-C-3	6.43	5.62		1.244		32.8	0.98	P
4-E/N-C-4	5.88	5.14		1.169		32.8	0.90	P
2-P/K-C-1	7.32	5.88	5.58	2.707	1.780	32.8	1.03	SP ;PO
2-P/K-C-2	5.64	4.53		1.313		32.8	0.79	SP ;PO
2-P/K-C-3	7.19	6.29		1.647		32.8	1.10	SP ;PO
2-P/K-C-4	6.43	5.62		1.532		32.8	0.98	SP ;PO
2-P/N-C-1	3.77	3.03	3.32	0.610	0.706	32.8	0.53	SP
2-P/N-C-2	4.53	3.64		0.740		32.8	0.64	SP
2-P/N-C-3	3.95	3.45		0.750		32.8	0.60	SP
2-P/N-C-4	3.60	3.15		0.722		32.8	0.55	SP
2-P/N-N-1	3.54	2.84	3.12	0.365	0.476	32.8	0.50	SP
2-P/N-N-2	3.95	3.18		0.555		32.8	0.55	SP
2-P/N-N-3	3.52	3.08		0.470		32.8	0.54	SP
2-P/N-N-4	3.88	3.39		0.514		32.8	0.59	SP
4-P/N-C-1	4.86	3.90	3.81	0.657	0.667	32.8	0.68	SP
4-P/N-C-2	4.71	3.79		0.662		32.8	0.66	SP
4-P/N-C-3	3.99	3.49		0.665		32.8	0.61	SP
4-P/N-C-4	4.62	4.04		0.686		32.8	0.70	SP

[a] Specimen identification according to Figure 3.3.
[b] Mean value for similar specimens .
[c] P = peeling off; SP = sudden peeling off and PO=push-out.

3.3.1.1. Effect of concrete strength on bond strength

For concrete with compressive strength approximately greater than 30 MPa, the bond failure occurs at the surface of the bamboo strips. Consequently, the bond strength bamboo-concrete does not depend greatly on the value of concrete strength, but rather on the bamboo strips' surface treatment properties. However, further investigation is required to analyse influence of lower strength concretes, where the bond failure mode changes and failure takes place at the concrete matrix interface.

3.3.1.2 Effect of resin type on bond strength

The resin type influenced bond strength and failure mode of the gravel coating layer and bamboo strip during push-out test (Table 3.3 and Figure 3.9). This tendency has been confirmed by the tests carried out in this study. The concrete strength was sufficient to limit failure to the gravel coating and bamboo surface.

When using polyester resin, all specimens failed in a sudden peeling off (SP) mode with failure taking place in the bamboo strip surface. In all cases, the bamboo surface cleaning procedure did not involve a change in failure mode but did improve the bond strength. Nevertheless, a change in failure surface did take place, involving more damage on the strip surfaces (see Figure 3.9). When using epoxy resin a peeling off of the whole layer of the gravel coating from the strip occurred, influencing response as shown in Figure 3.5-4.8. The mean bond strengths, as well as the maximum and minimum experimental values obtained for the different surface treatment, are shown in Figure 3.4a. Although the increase of bond strength depends on the type of treatment and resin, where variations of up to 2.0 are obtained as shown in Figure 3.4b, indicating the effect of the resin on bond strength.

a) b)

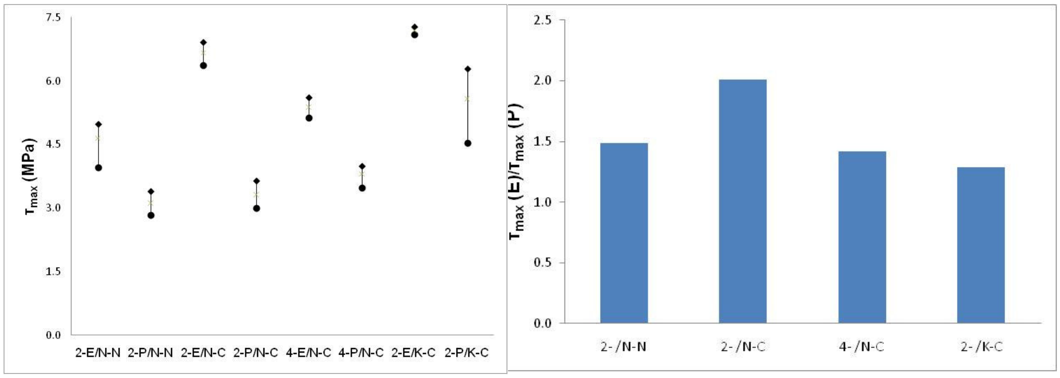


Figure 3.4- (a) τ_{max} for specimens when using epoxy or polyester resin (b) τ_{max} increase ratio due to change of resin

3.3.1.3. Effect of surface treatments on bond strength

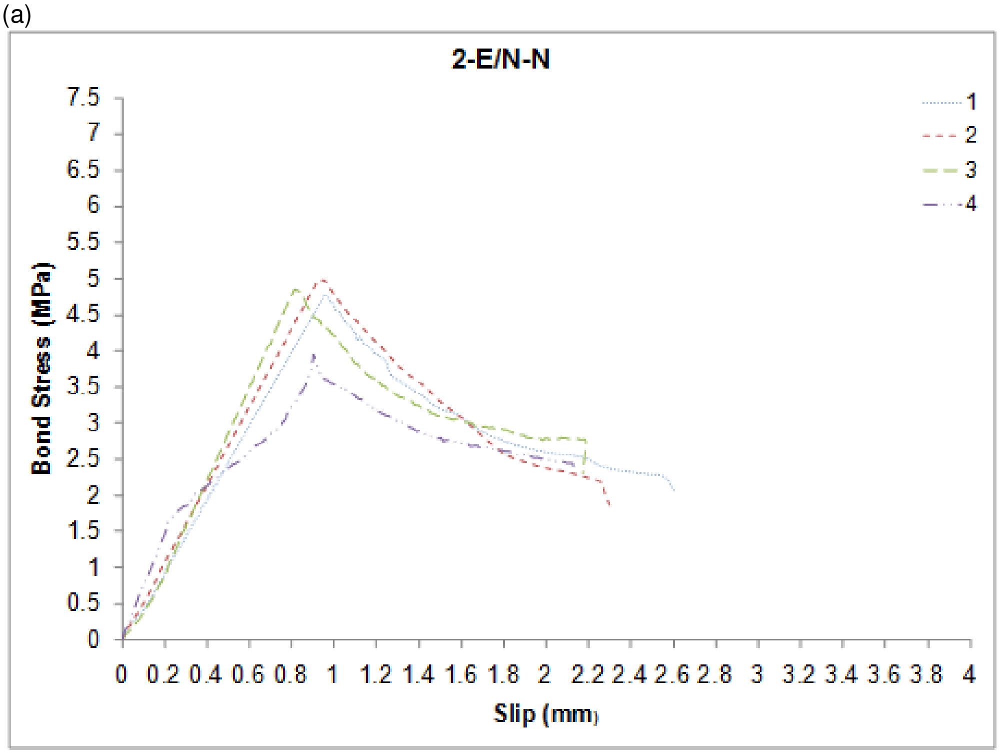
The bamboo surface treatments used in this study (see Table 3.3 and Figure 3.1) are designed to improve the bond strength of bamboo-concrete and as well as waterproofing bamboo strips. This is achieved in different ways. Due to the importance of the bamboo strip surface treatment on bond behaviour, it is worth comparing the bond strengths obtained for the different treatments. In the case of N-C strips (2mm or 4mm gravel size), the higher bond strength is obtained with the 2 mm gravel size, irrespective of the resin. In both cases, strip surface can be considered relatively undeformed, with bond strength strongly dependent on the friction resistance provided by the bamboo surface cleaning treatment. The highest bond strength is obtained with K-C strips when using epoxy resin and can be attributed to the existence of bamboo node on the strip. For the rest of treatment (2-E/N-N and 2-P/N-N), with non-bamboo surface cleaned and without a node, lower bond strengths are obtained because there is little bearing resistance. Nevertheless, it is worth mentioning that the weakest and best treatment study in this work improved by 1.14 and 2.61 times respectively the bond strength obtained previously for Acha (2002) [35].

The effect of surface treatment can also be analysed with regard to the gravel size on coating layer. The results show higher bond strength when using 2mm gravel size regardless of the resin. When using 4mm gravel in the coated layer, larger gaps between the small aggregate are present, producing higher stress concentrations along the bamboo surface strip; at these stress peaks debonding is initiated. Also, using 4mm gravel the coating layer is thicker producing further internal tension in the layer, which can damage the coating layer before the debonding with the bamboo surface occurs.

3.3.2. Bond stress–slip relationship

The global behaviour of the bond stress–slip relationship is characterised by an initial increase in the bond stress with little slippage. This is followed by softening once the maximum bond stress is attained. Up to the failure, bond can be attributed to bearing (for cleaned and bamboo node), adhesion and friction between the bamboo surface and gravel coating. Once the adhesive bond fails, different behaviour was observed for different surface treatments. Specimen curves for each tested group are shown in Figures 4.5-4.8 to illustrate the bond stress–slip relationship obtained for the different specimens.

(a)



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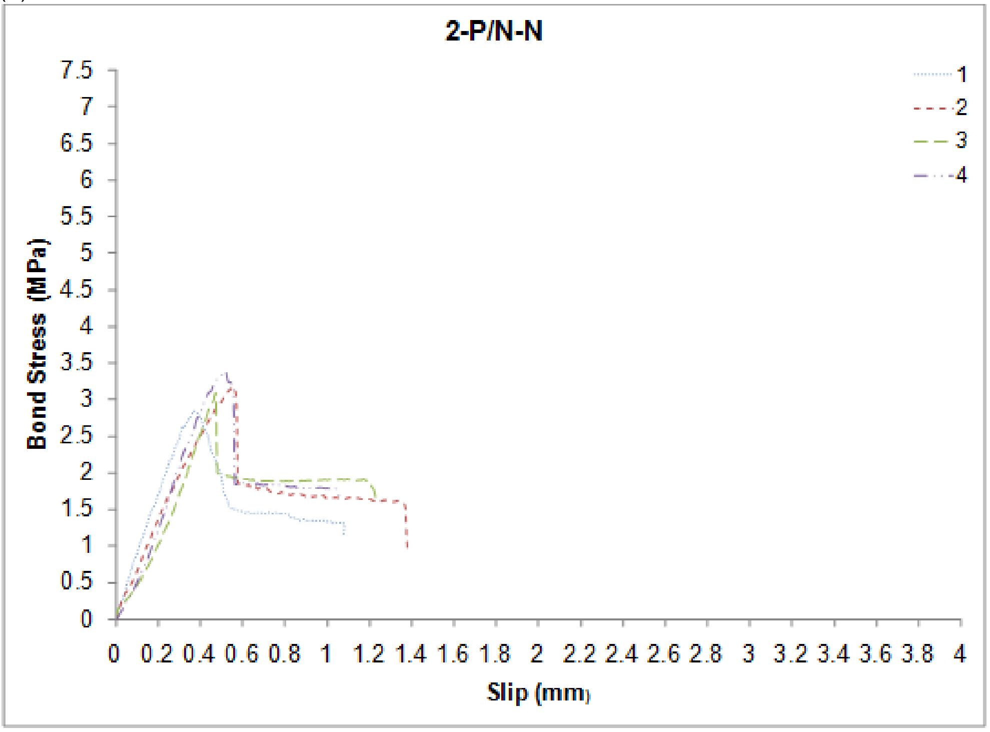
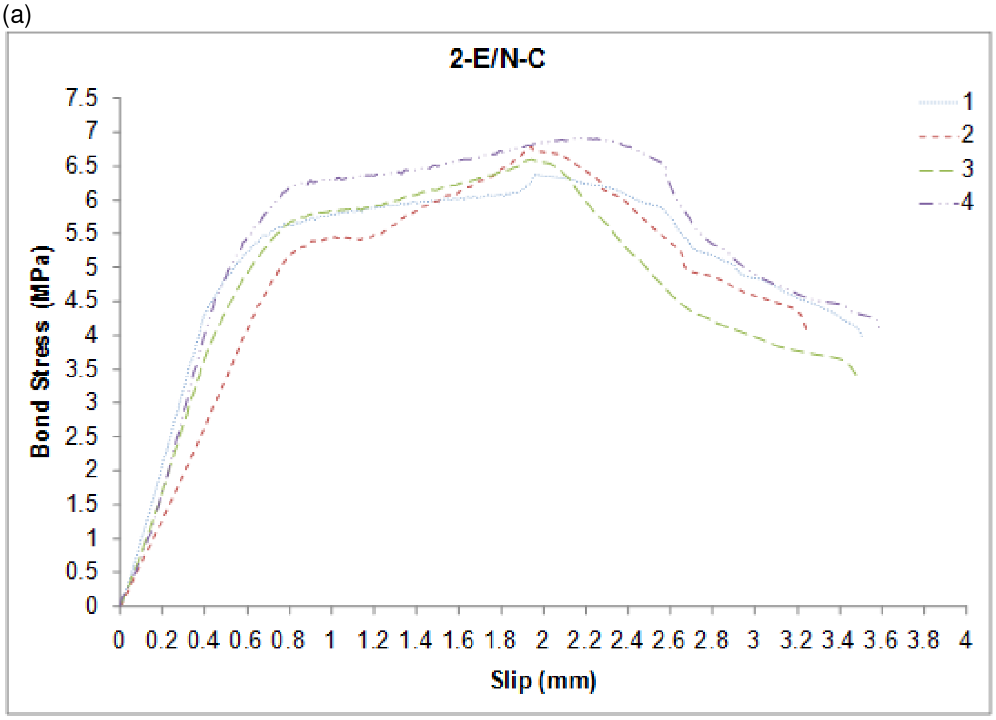


Figure 3.5- Specimens bond stress–slip curves for (a) 2-E/N-N and (b) 2-P/N-N groups

(a)



(b)

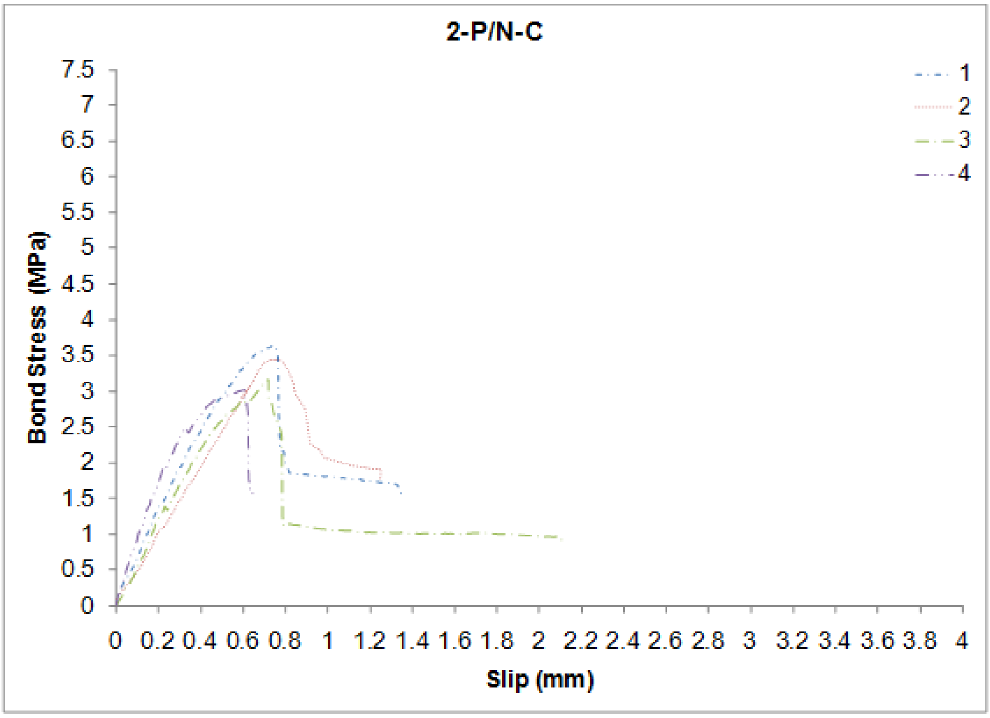
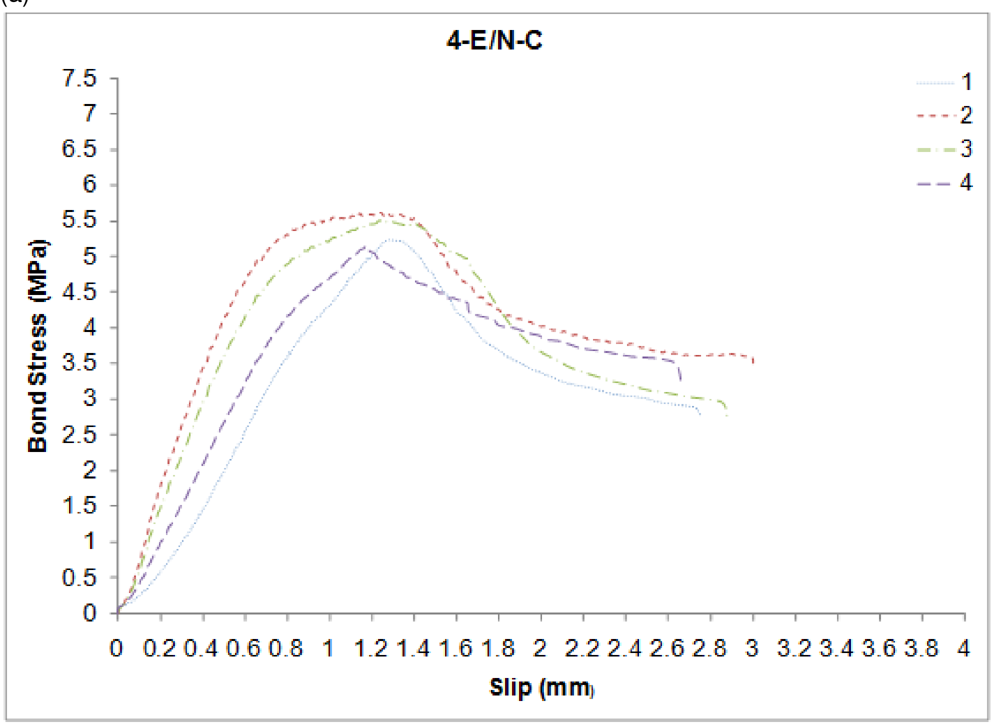


Figure 3.6- Specimens bond stress–slip curves for (a) 2-E/N-C and (b) 2-P/N-C groups

(a)



(b)

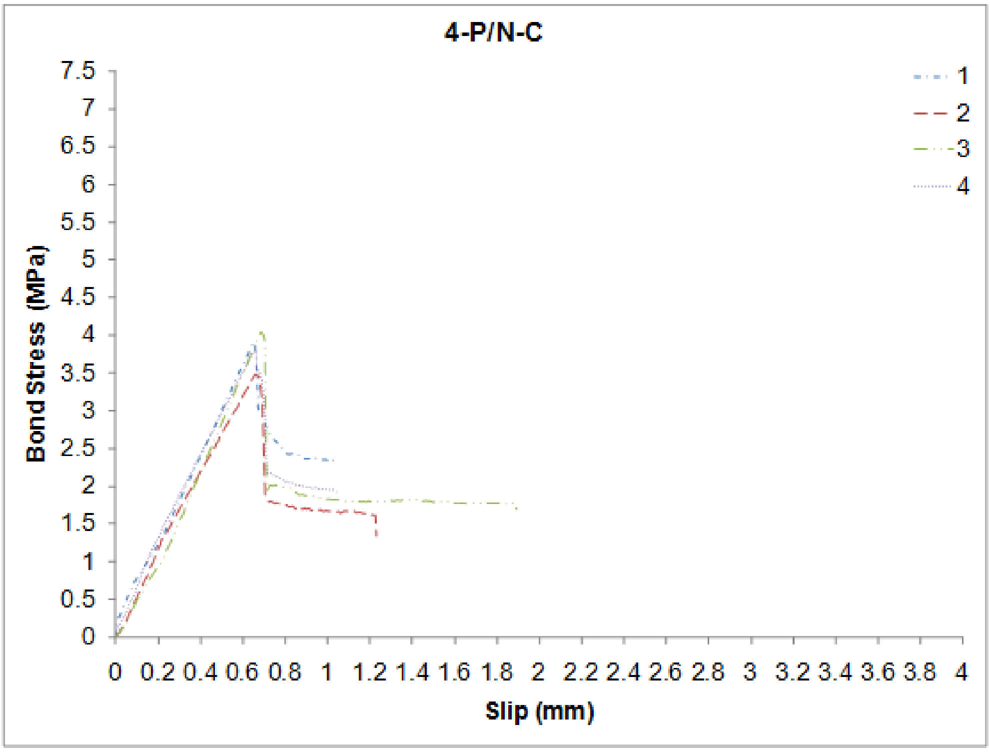
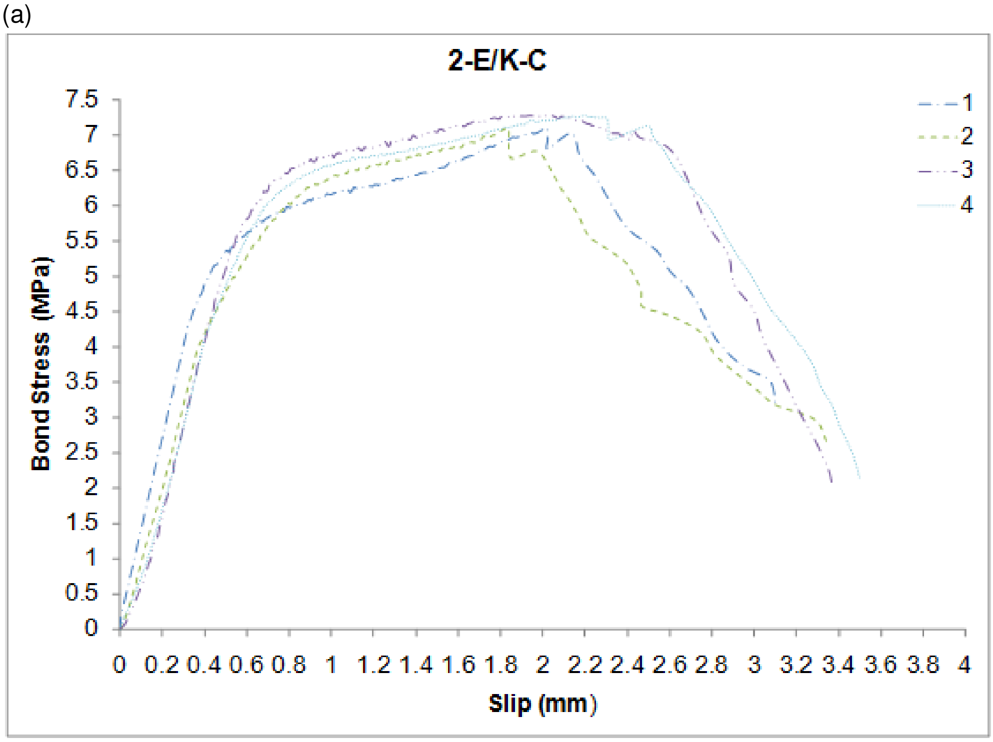


Figure 3.7- Specimens bond stress–slip curves for (a) 4-E/N-C and (b) 4-P/N-C groups

(a)



(b)

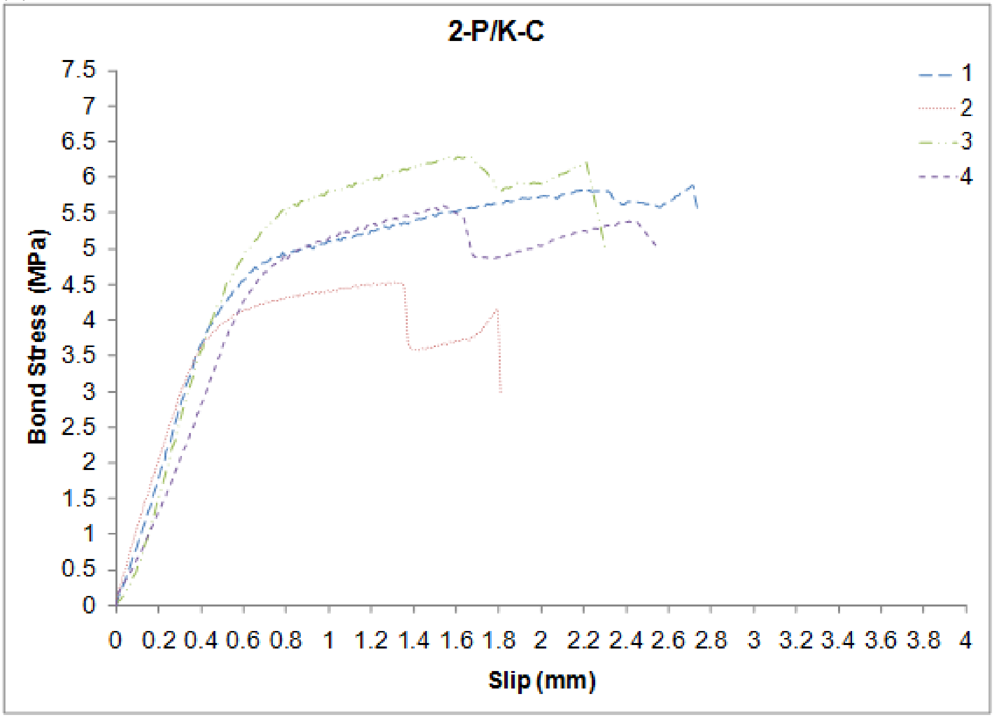


Figure 3.8- Specimens bond stress–slip curves for (a) 2-E/K-C and (b) 2-P/K-C groups

For bamboo strips without node (N-N and N-C), the load transfer is provided by friction and is therefore strongly dependent on transverse pressure. Under loading the friction decreases as the strip is pushed further out and the contact surface is damaged. For cleaned strips (N-C), Figure 3.6 and Figure 3.7, an initial good bond performance with high bond strength, almost linear behaviour and a relatively small slip at the ascending branch of the stress–slip curve is observed. Cleaning the bamboo surface leads to an increase in the chemical bond, as reported in [35]. Once the bond strength is reached, the whole small gravel coating layer debonds from the bamboo strip. When using polyester resin an abrupt decrease is observed as shown in Figure 3.5b-4.7b. Nevertheless, when using epoxy resin a softening decay takes place. This phenomenon is observed regardless of the gravel size coating studied (2 mm and 4 mm). However, for the 2 mm gravel coating the decay is smoother. When using cleaned bamboo strips (see Figure 3.9b) push-out of tiny indented bamboo from the strip takes place, but for non-cleaned strips, a peeling off of whole coating is observed (see Figure 3.9a).

The sudden unloading paths observed in Figure 3.5-4.8 after the maximum bond stress shows that the polyester resin in the gravel coated layer has a stiffener property than epoxy resin.

The non-cleaned bamboo strips (N-N) presented a very smooth surface. Consequently, bond strength is based primarily on chemical adhesion and a small friction force, with low mechanical bearing forces expected. However, the behaviour of N-N strips differs from the behaviour of N-C strips. The maximum bond stress is lower than N-C and occur with more slip when considered the same bond stress. It is obtained when the chemical adhesion is lost (see Figure 3.5). The push-out of tiny indented bamboo surface observed in N-C does not take place in N-N strips and, therefore, after the peak, the bearing resistance decreases swiftly (most markedly when using polyester resin). However, because of its smoother surface, the N-N strip bond strength is smaller than the N-C strip bond strength, with the difference being even larger when using 2 mm gravel coating surface treatment.

It is evident that for bamboo strips without node (N-N and N-C), surface cleaning plays a very important role in the bond strength and this importance increases when using 2 mm gravel size aggregate. Moreover, it should be noted that the failure mode of treated strips is always located at the interface between the whole gravel coating layer and bamboo surface strip.

For bamboo strip with node and cleaned (K-C), the crushed concrete sticking to the front of the nodes (see Figure 3.9c) exerts a wedging action similar to deformed steel bars. As a consequence, the surrounding concrete exerts a confinement action on the strip. Depending on the confinement, push-out or splitting failures occur. Therefore, the geometry of the strip is very important for the bond stress-slip response. When using polyester resin, bearing resistance decreases, producing a more abrupt decay in bond stress after the peak. However, the bamboo node develops larger bearing resistance while the strip is solicited, increasing the bond strength. This explains the difference in the bond stress-slip curve obtained when using K-C strips compared to N-N and N-C. After the point where the chemical adhesion is lost, the bamboo node increases the bond strength before a softening decay. This increase is related to the re-engaged mechanical interlock after the debonding of coating treatment, improving the mechanical contribution of treated bamboo strips (mainly those with polyester resin treated). A similar undulating behaviour has also been reported for steel bars with ribs as indicated in the CEB-FIP Model Code 90 [60]. The shape of the bond stress–slip curves obtained for K-C strips (shown in Figure 3.8) is significantly different from the others. The ascending branch of the curve is clearly stiffer and the slip values corresponding to the bond strength are smaller than other bamboo strips tested. Push-out of node from the strip and peeling off of gravel coating layer was observed in failure. Nevertheless the bamboo node region with the weakest stem fibres plays an important influence on the bond stress and bearing resistance as reported previously [38].

For comparison purposes, bond stress concrete-steel rebars was consulted in the literature. For similar concrete strength and approximately equivalent cross section area rebars used in this study, the bond stress for steel bars with and without ribs are 2.2 MPa and 14.1 MPa respectively [61, 62].

N-N N-C K-C

a b c

Figure 3.9- Examples of failure modes: (a) peeling off of natural (not cleaned) strip surface; (b) peeling off of cleaned strip surface; (c) peeling off and push-out of strip with node and cleaned

3.3.3. Initial bond stiffness

The influence of the different types of treatment and the bamboo node contribution on the initial stiffness of the bond-slip curve is analysed in this section. The ascending branches of bond stress versus slip curves for N-N, N-C and K-C strips, when using epoxy or polyester resin, are analysed. Average curves of similar specimens have been calculated in order to generalise the different effects of strips treatment (see Figure 3.10). N-N strips are expected to develop greater slip values than the others strip treatment under similar push-out loads, since their surface are natural, therefore, the micro particles of cellulose that protect the bamboo strip fibres form a flat and smooth surface and also the dust inhibits development of a good bond. This is confirmed by the results shown in Figure 3.5 and Figure 3.10.

Comparing with the behaviour from [62] for steel bars, for lower forces, the slip of the steel rebars is negligible. However, for bamboo strips, as soon as force is applied, the slip between the whole gravel coating layer and the bamboo strip can be measured, regardless of the surface treatment. The initial ascending branches for the different surface strips treatment used in this experimental study are also plotted in Figure 3.10. Specimens of K-C strips present the highest initial stiffness. However, for the remaining cleaned strips, a higher stiffness is obtained when using 2 mm gravel and epoxy resin. Types 2-P/N-C and 4-E/N-C have a similar initial stiffness, while 4-P/N-C has the smallest initial stiffness for the cleaned bamboo surface group. The influence of the bond resin on the initial stiffness can be observed and mainly when the gravel size is 2 mm or at existence of the bamboo node as shown in Figure 3.10.

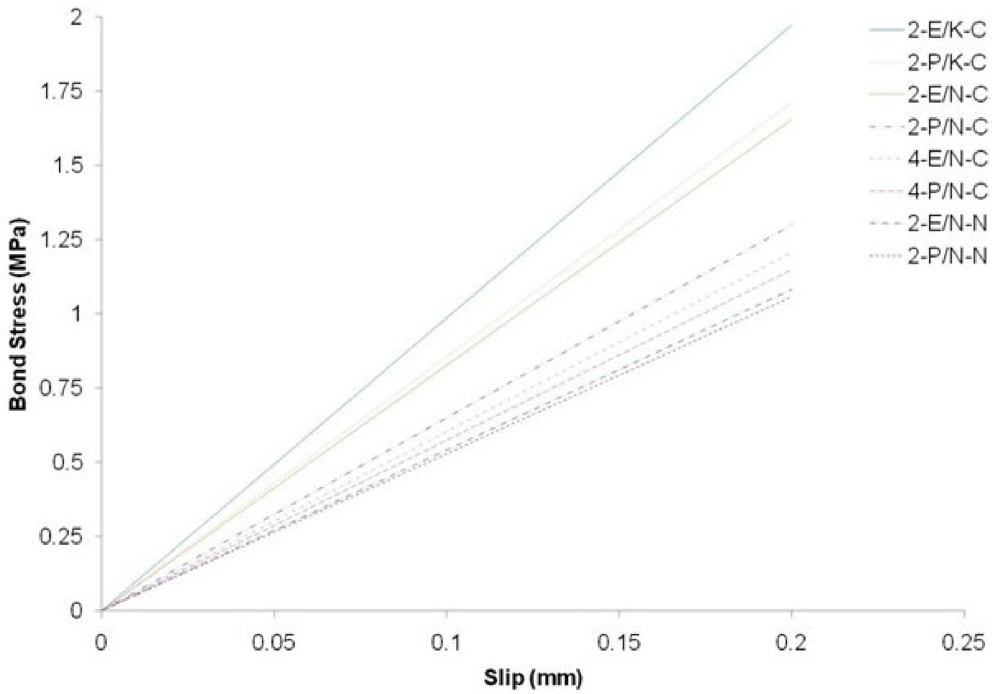


Figure 3.10- Influence of type of bamboo strip surface treatment on the initial stiffness. Bond stress- slip curves of N-N, N-C and K-C

3.4. Conclusions

This study has been aimed at improving the bond characteristics of treated bamboo strips for concrete reinforcement, by means of applying different treatments to the bamboo surface. The treatment made using 2 mm aggregate, epoxy resin and cleaning bamboo surface procedure, with or without node, lead to significantly better performance. Bond strength is improved on average 4.5 times more than the natural bond stress of bamboo when embedded in concrete, as well as improving waterproofing of the bamboo. Bamboo surface cleaning plays a very important role in the bond strength and this importance increases when using 2 mm gravel size aggregate. Nevertheless as the bamboo node region has got the weakest stem fibres it plays an important influence on the bond stress and bearing resistance. These bamboo strips surface treatment allow the use of bamboo strips as concrete reinforcement safely.