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Limeboo: Lime as a Replacement for Cement in Wall-Framing Systems with Bamboo-Guadua (Bahareque Encementado)

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Abstract. Traditional construction systems with the bamboo species *Guadua angustifolia* Kunth (Guadua) are standardized under the Colombian code for seismic-resistant buildings [1]. These systems are regarded as highly environmentally friendly due to their intensive use of Guadua in the supporting structure and walls. In particular, the plastered cane building system or ‘*bahareque encementado*’, which provides a low-cost and low-technology alternative for two-storey dwellings, commonly uses round Guadua for the frame and riven Guadua boards (*esterilla*) for covering the frame. However, this wall-framing system relies heavily on cement renders for providing combined structural action to resist lateral loads, protecting the material against weathering and ensuring a flat surface for construction finishes. Thick cement renders contribute greatly to the wall mass and together with the foundations result on the highest negative environmental impact in traditional wall-framing construction with Guadua. Therefore, the reduction of the use of cement or its complete replacement for alternative binders in the wall-framing *'bahareque'* system is a key point for environmental improvement. Widely available materials such as lime, which have less energy intensive production-processes present an alternative to cement. Moreover, lime offers improved breathability within the building and behaves more elastically than cement. This paper explores the potential use of lime as a replacement for cement mortars in *'bahareque'* systems and analyses Guadua’s anatomical and chemical features when mixed with lime. The paper describes a “cold process” in which no high temperatures are involved for the improvement of the bonding between lime and bamboo.

Introduction

Plastered cane wall system: *Bahareque encementado*. The wall-framing system with *Guadua angustifolia* Kunth (Guadua) for one and two storey dwellings is referred as to ‘*Bahareque encementado’* in the Colombian construction code [1]. It is defined as a system composed of a Guadua or Guadua and timber skeleton, and a sheathing of riven Guadua (esterilla) boards (Fig. 1) nailed to the skeleton and covered with a cement render applied over a steel mesh [1, 2]. Frame and walls together result in a shear wall response. The cement render contributes to this combined structural action for resisting lateral loads, providing protection against weathering and ensuring flat surfaces for building finishes.

Guadua building systems such as *bahareque encementado* are regarded as highly environmentally friendly due to the intensive use of Guadua. Typically, this system uses approximately 50% of round Guadua for the skeleton and 50% of riven Guadua boards to cover the frame. However, the high variability of round and riven Guadua results on irregular surfaces that need thick cement renders to achieve uniform wall surfaces. The use of a thick sand/cement render in the Guadua's structural wall framing system accounts for 85% of the wall mass [3]. This is equivalent to a total sand/cement render mass in a two storey 35m^2 house of approximately 15,000kg, whilst the total weight of Guadua used is 1,800kg. Murphy and colleagues [3] also highlight that the overall use of aggregates, cement and steel contributes to about 95% of the environmental impact in Guadua construction. This impact is mainly attributed to the foundations and walls that use materials such as: sand/ballast, cement and steel. Cement renders are therefore, a key topic for environmental impact reduction in *bahareque encementado* systems using Guadua. Thus, an alternative for reduction of this environmental burden is the use of wall render materials with less embodied energy during the production stage such as lime. Compared to the production of cement, the production of air lime uses temperature ranges between 900°C and 1000°C, which are about 30% lower. Furthermore, unlike cement, lime absorbs CO_2 during the curing process and improves permeability of wall renders.

Figure 1. Plastered cane wall-framing system

Use of lime as sustainable building material

The term "lime" refers to a quite large family of inorganic binders including air limes and limes with hydraulic properties. Air limes have the property of hardening by reaction with atmospheric CO_2, whilst those hardening by reaction with atmospheric CO_2 and water are considered limes with hydraulic properties (hydraulic limes).

Historically, lime has been used in combination with other materials to form a composite structure, provide specific characteristics, or stabilize mixes. The use of lime in adobe and rammed earth constructions results in less plastic soils with less moisture uptake and improved mix stability (thus, increased strength in compression; [4]). Traditional building techniques with straw bales have been improved recently and lime is being used for plastering straw-bale walls or binding hemp shiv in non-load bearing walls. The result of these combinations are non-structural lightweight walls with thermal and acoustic insulation properties [5]. Fire resistance and biological decay protection are also achieved. Straw-bale building systems such as Modcell® which use a structural timber frame, are considered to store up to 135kg of CO_2/m^3 [6]. This is a desirable feature for a sustainable building material. Furthermore, Bevan and Woolley [5] state that the hygroscopic characteristic of these composites can lead to health benefits by reducing condensation and regulating humidity.

Traditional '*bahareque'* and wattle and daub systems have also utilized lime, either mixed with sand and fibrous materials for rendering/in-filling the walls, or diluted in water as an external wall protective coating (lime-wash). However, little research has been conducted on the chemical and physical interaction between lime and bamboo and assessing its suitability as cement replacement on '*bahareque'* systems.

Hydraulic reactions in lime based materials and silica content in bamboo

Air limes and hydraulic limes have different chemical, physical and mechanical characteristics but have a common high calcium hydroxide ($Ca(OH)_2$) content [7]. Calcium hydroxide is a non-combustible compound with low solubility (about 1.7g/l; [8]) responsible of providing a highly alkaline environment (pH≈12.6 at 20°C) when dissolved in water [9]. Dissolution of $Ca(OH)_2$ is an important stage of carbonation that is the most important chemical reaction in mortars containing air lime, and the reaction that provides the long term strength in mortars containing hydraulic lime.

Calcium hydroxide dissolution is important also for the reaction between lime and the hydraulic additives that can be added to air lime for producing an artificial hydraulic lime. The highly alkaline environment produced by the $Ca(OH)_2$ dissolution significantly increases silica (SiO_2) solubility [10]. Silica is one of the main oxides responsible for the hardening process of lime in water. In aqueous solution both compound, lime and silica dissolve forming calcium ions (Ca^{2+}) and mono-silicic acid (H_4SiO_4) that react together forming calcium silicate hydrates (CSH) which is responsible for the short term hardening of hydraulic lime:. In order to obtain a Si-rich environment, however, the SiO_2 must be in an amorphous state (e.g. non-crystalline). Therefore, silica has to be chemically or thermally treated in a process that transforms crystalline phases into an amorphous state. The most common treatment is a thermal process that requires high energy input and depending on the fuel source used for heating the material, results on high CO_2 emissions. Availability of naturally amorphous silica is therefore, highly regarded in the modern construction industry.

An amorphous form of hydrated silica ($SiO_2 \cdot nH_2O$) is fixed in plants through absorption by roots and a chemical process that polymerizes mono-silicic acid from the soil [11]. Silica is found as part of the chemical composition of some plant cells and referred to as silica cells [11, 12]. The walls of silica cells are highly silicified and the presence of silica in plants, their shapes and function have also been extensively studied by Mehra & Sharma [13], Bonnett [14] and Dayanandan and colleagues [11].

The presence of silica in bamboo has been reported by several authors [12, 15, 16, 17, 18, 19]. Liese [12] highlights the structural support that is given to bamboos by the occurrence of short silica cells along with cork cells and the stomata in the epidermal layer of stems. This author also remarks that the total silica content by weight on bamboo reaches up to 5% of the total mass with its highest concentration in the epidermis (e.g. silica content in the epidermis of the bamboo species *Bambusa vulgaris* and *Schizostachyum lumampao* are 1.5% and 6.4%, respectively). Content of SiO_2 in foliage of *Guadua angustifolia* measured by Herrera-Giraldo and colleagues [15] ranged between 1.7% and 2.6% of the dry weight basis (in ash). In general, the amorphous silica content in bamboo increases towards the top and along the periphery of the stem, whereas in the radial direction towards the pith (inner part) it is almost zero [12]. Lux and colleagues [17], evaluated the accumulation of silicon in leaves and roots of the bamboo species *Phyllostachys heterocycla* Mitf where its presence protects the plant against damage and insects, and assists the rhizomes in spreading underground in difficult soil conditions.

In construction with bamboo, the presence of silica is known to cause wear of cutting tools [12, 20]. For instance, due to intense saw wearing, the use of diamond saw blades is necessary in cutting Guadua stems. Nevertheless, there is potential for using organically synthetized amorphous silica for construction. Rajamma and colleagues [21] underline that waste from agricultural resources contains high amounts of amorphous silica that can promote pozzolanic reactions with cementitious binders. Ash from biomass sources such as such as rice husk ash, bagasse ash, saw-dust ash and palm oil fuel ash usually contain high levels of SiO_2 [21].

The controlled use of silica contained in bamboo can contribute to the pozzolanic reaction that improves the cementitious qualities of lime. Dwivedi and colleagues [22] demonstrated that the use of bamboo leaf ash (BLA) increased the amount of CSH through reaction with $Ca(OH)_2$ during hydration of Portland cement. Amu and Babajide [23] found that the use of BLA increased the strength of lime-stabilized soils. Furthermore, lime has been traditionally used for the preservation of bamboo culms, due to its high alkalinity.

This paper aims to provide the first experimental evidence of the possible reaction between lime and the amorphous silica contained in the external part of the culm wall of Guadua bamboo. The research investigates the development of a "cold" process (i.e. without use of treatments with high energy consumption) for the use of lime as replacement of cement mortars in '*bahareque*' systems.

Materials and methods

Chemical reactions between silica and lime were studied using six samples of riven Guadua ('*esterilla*') obtained from the middle part of a single cane. Control samples from the same cane with no-lime treatment were also studied. Two air limes, a calcic lime CL90S (according to the European Standard EN 459-1 [24]) produced by Singleton Birch Ltd (UK) and a dolomitic lime DL85-S2 [24] produced by Calce Piasco spa (Italy) were selected as high alkaline binders together with a natural hydraulic lime NHL 3.5 produced by Singleton Birch Ltd.

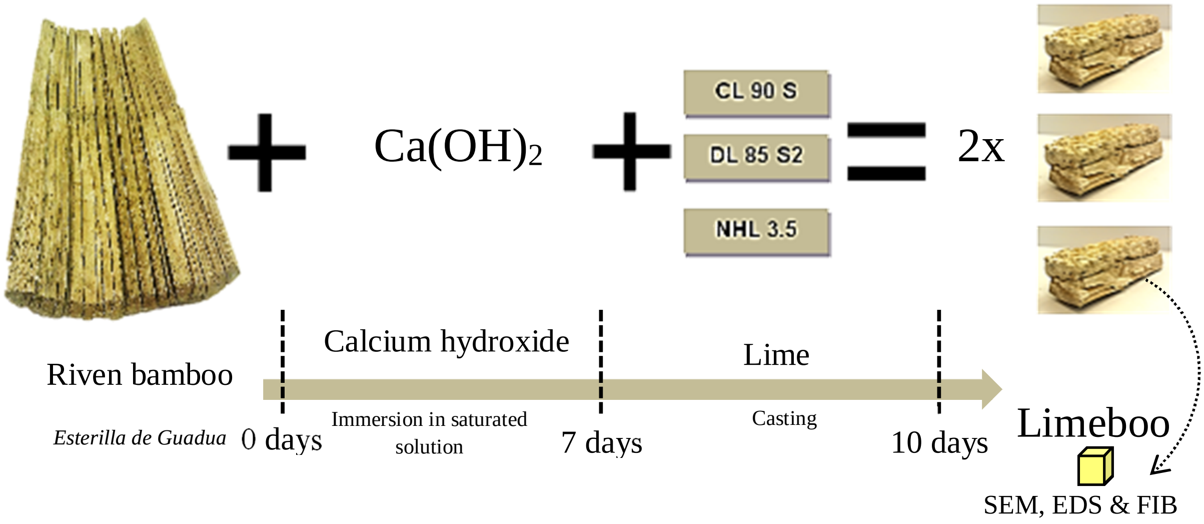

Figure 2 Preparation process of samples for SEM, EDS and FIB

The samples were pre-treated by immersion in a saturated aqueous solution of $Ca(OH)_2$ for 7 days before applying the lime based mixture to the surface of the riven Guadua (Fig. 2). This treatment resembles a traditional practice aimed to produce an anti-fungal action [4] and most importantly, triggers a chemical attack that breaks some of the cells in the outer part of the culm. This potentially provides Ca^{2+} ions access to the underlying silica cells. Subsequently, the outer part of the culm of each sample was plastered with a lime based mixture and cured for 10 days at about 20°C and 65% RH in a conditioning room. The resulting lime and bamboo-Guadua mix was called *Limeboo*. At the end of the curing process of the Limeboo samples, the hardened lime was manually removed from the surface of the riven Guadua and small cubes were cut for further interfacial analysis (where the reaction between $Ca(OH)_2$ and SiO_2 would be expected to have taken place).

Microstructural characteristics of control and Limeboo samples were investigated using electron microscopy before and after treatment. The chemical composition of different areas within the samples was investigated by Energy Dispersive X-ray Spectroscopy (EDX). These analyses were carried out using a JEOL JSM6480LV scanning electron microscope (SEM) coupled with an Oxford INCA X-ray analyser. The latter allowed the mapping of elements on the focussed section of the samples. Data was collected and qualitative analysis of the components was performed with INCA Energy 350 software from Oxford Instruments. The samples were kept under vacuum for one week and then attached to removable microscope holders using carbon tape. Prior to SEM imaging and EDX elemental analysis, a 30nm thick coating of gold was applied using an Edward Sputter S150B coater.

Following the X-ray mapping of the control samples a more detailed analysis of the SiO_2 and $Ca(OH)_2$ fixation in the cell walls of Guadua was conducted using an FEI Strata FIB-201 Focused Ion Beam (FIB) workstation. This technique allowed milling of the lime/bamboo interface and high-resolution imaging of the cell wall structure of Guadua samples. A gallium ion beam was used to mill and cut into the sample by sputtering in the defined areas of interest. Imaging of specific regions of the Guadua cortex where the silica content appeared to be higher (from prior SEM imaging) was undertaken. 5mm cubes were held in a vacuum for one week and sputter coated with gold before observation. The beam current was adjusted for good quality milling of the surface and high resolution imaging. The gallium ion energy was 30keV.

Results and discussion

The microstructure and the distribution of element silicon (in the form of silica) within the sections of the outermost and innermost parts of the Guadua stem have been imaged. Figure 3a shows the microstructure of a control sample from an outer section of a sample of Guadua with several vascular bundles, whilst Fig. 3b illustrates an EDX map and an EDX spectra of the same section. The upper right corner of the EDX map in Fig. 3b exhibits a high concentration of silicon in this area of the cortex of Guadua. The EDX spectra on Fig. 3b reports the presence of silicon (Si) together with potassium (K), carbon (C) and oxygen (O).

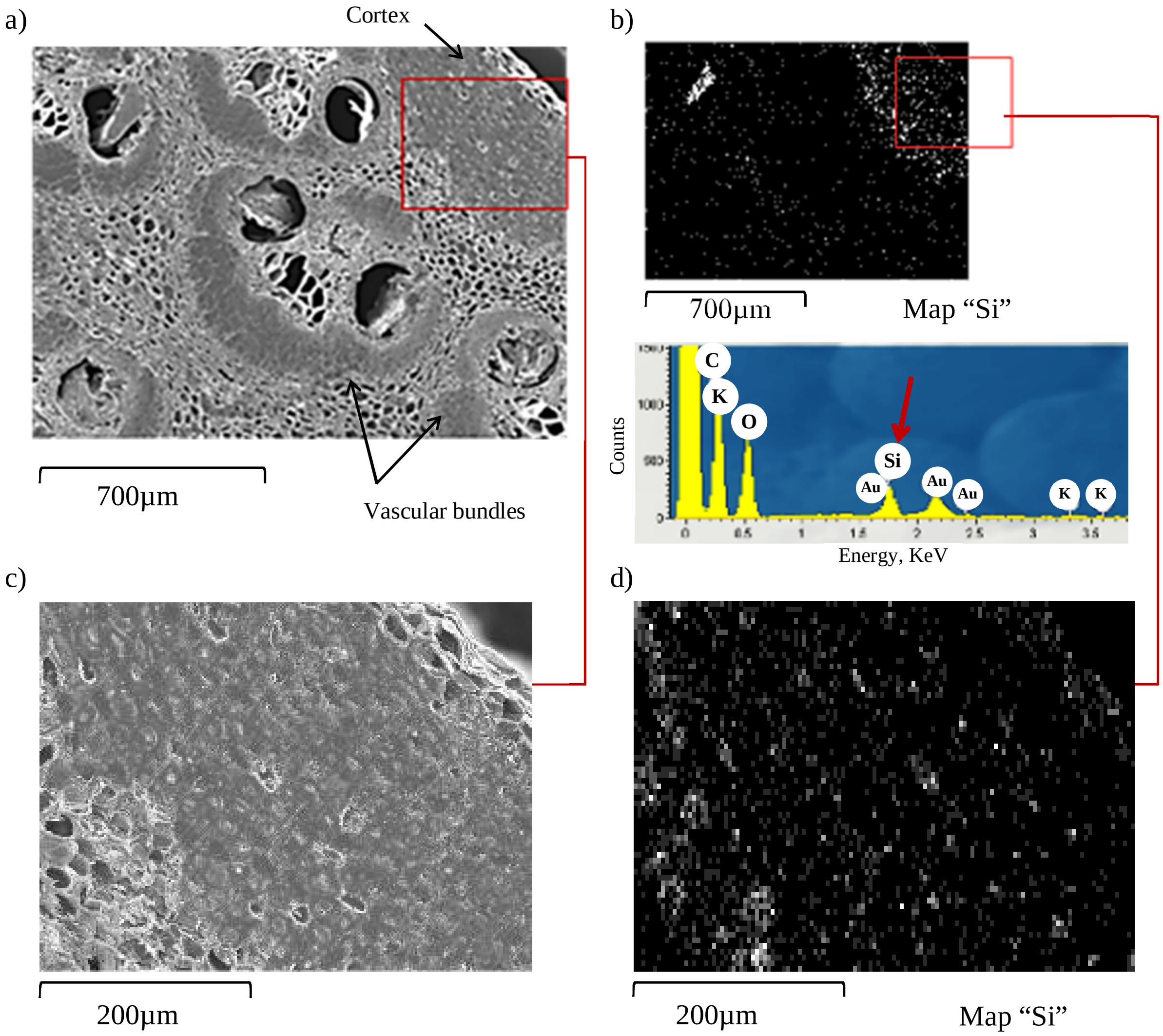

Figure 3 Elemental compositional analysis of a typical outer section of Guadua with no-Pre-treatment. a) Cross section of several vascular bundles near the cortex. b) X-ray elemental map of Si and EDX spectra of the same cross section. c) Close-up of the area marked by the red rectangle in image a. d) X-ray elemental map of Si of the area imaged in c.

This is in agreement with results obtained by other researchers [20, 25, 26] regarding the chemical composition of different bamboo species near the cortex. A small lump of Si of about 200µm length at about 800µm from the external surface is also observed in Fig. 3b. This lump corresponds to a section removed from the outer layer during sample preparation. Figure 3c and 3d are SEM and EDX images at higher magnification of the areas within the red rectangles in Fig. 3a and 3b, respectively.

Figure 4a indicates the presence of Si in a 100µm wide section of the Guadua cortex, which was imaged at high magnification. A detailed elemental analysis of this image, which is indicated by a red rectangle in Fig. 4a, illustrates a high concentration of Si and O within Guadua's epidermal cells (Fig. 4b and c). These cells can be regarded as silica cells.

The distribution of Si within the inner layer of the Guadua wall is shown in Fig. 5. Figure 5a shows the microstructure of the inner layer of the Guadua wall characterized by a different cellular structure and a more scattered distribution of Si (Fig. 5b).

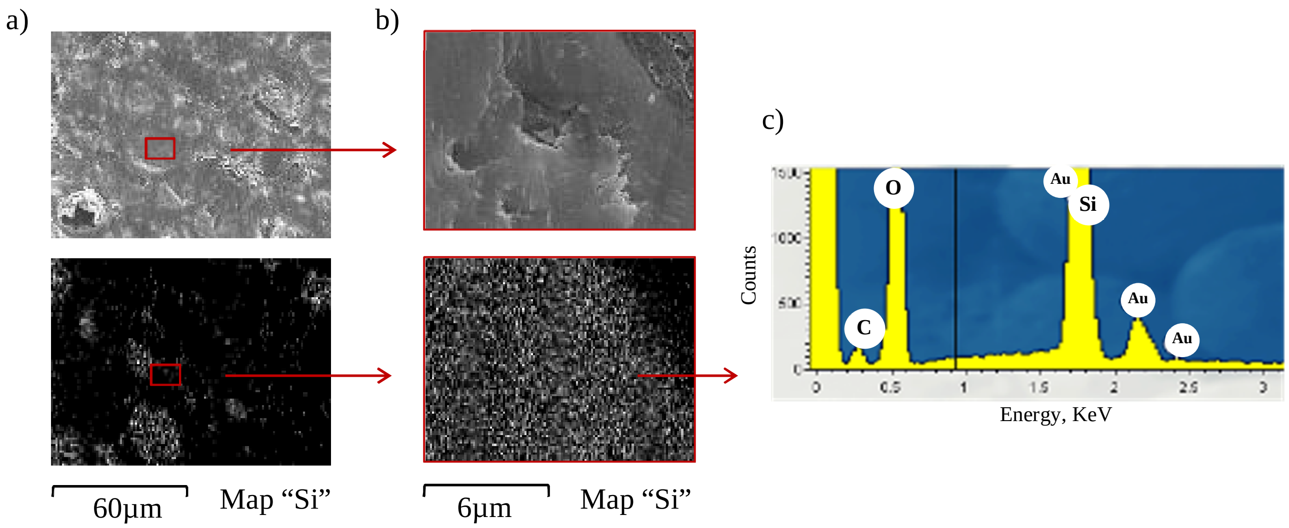

Figure 4 Silicon composition analysis of an outer part section of Guadua with no-pre-treatment. a) Section of 100µm wide. b) Section of 10µm wide. c) EDX spectra of image b.

A sample from the outermost part of Guadua was imaged using a FIB. A hole 40µm long, 20µm wide and approximately 20µm deep was milled into the surface of the sample by the ion beam and the internal cell wall structure was exposed (Fig. 6a). Darker zones on the polylamellate cell walls were observed, which suggested the fixation of an inorganic material on these layers. Figure 6b and Fig. 7 illustrate these observations from the same sample.

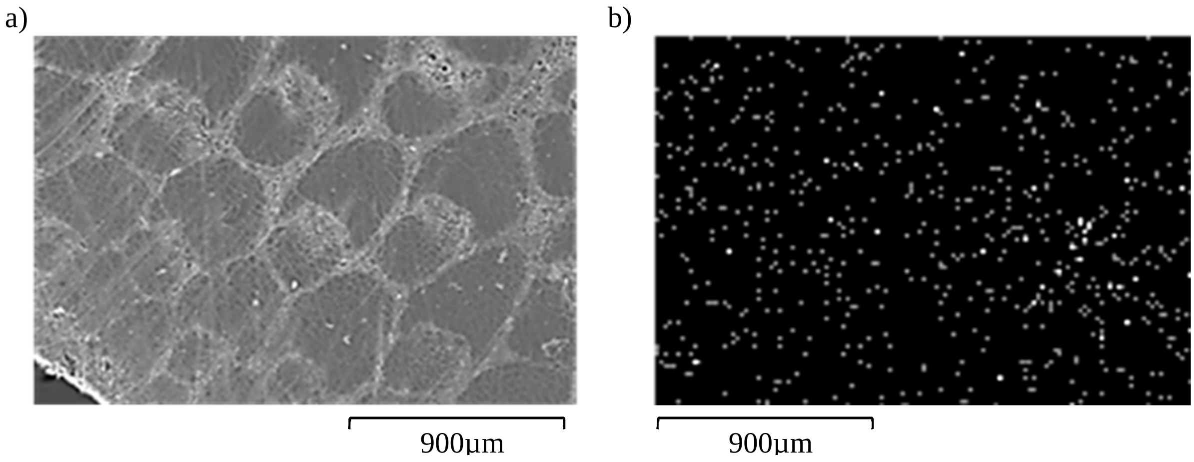

Figure 5 Elemental composition analysis of an inner part section of Guadua with no pre-treatment. a) Cross section of vascular bundles near the pith (innermost part). b) X-ray map of Si.

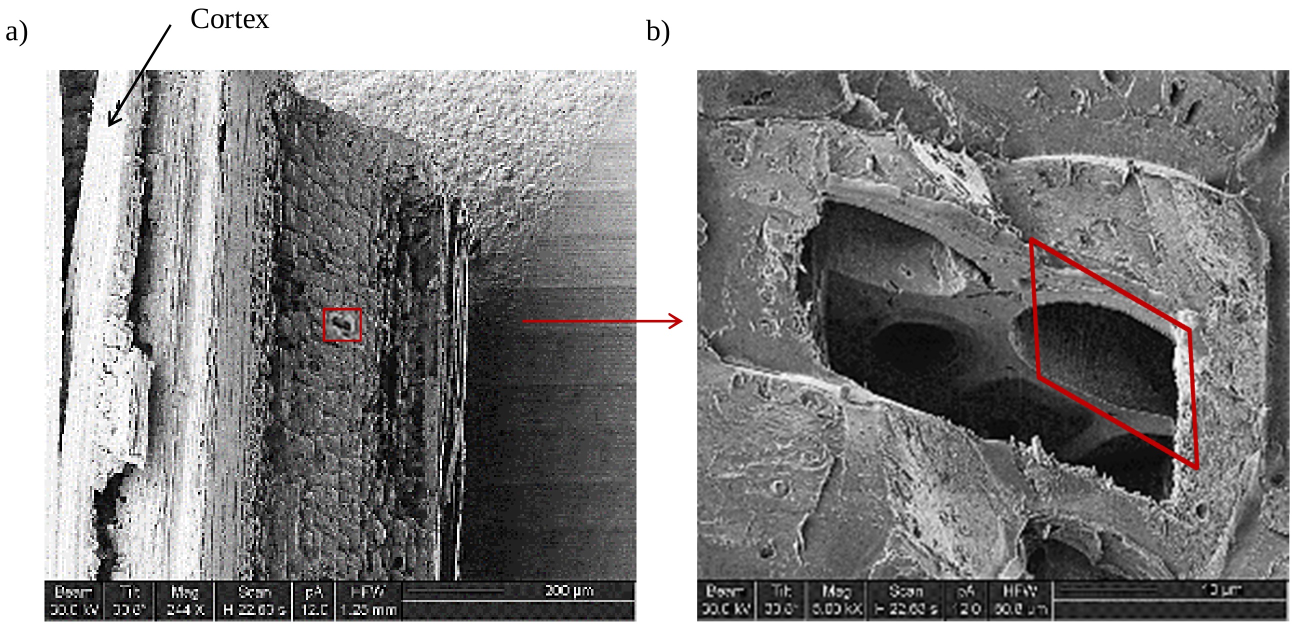

Figure 6 Cut through the cell structure of a Guadua sample near the cortex using FIB

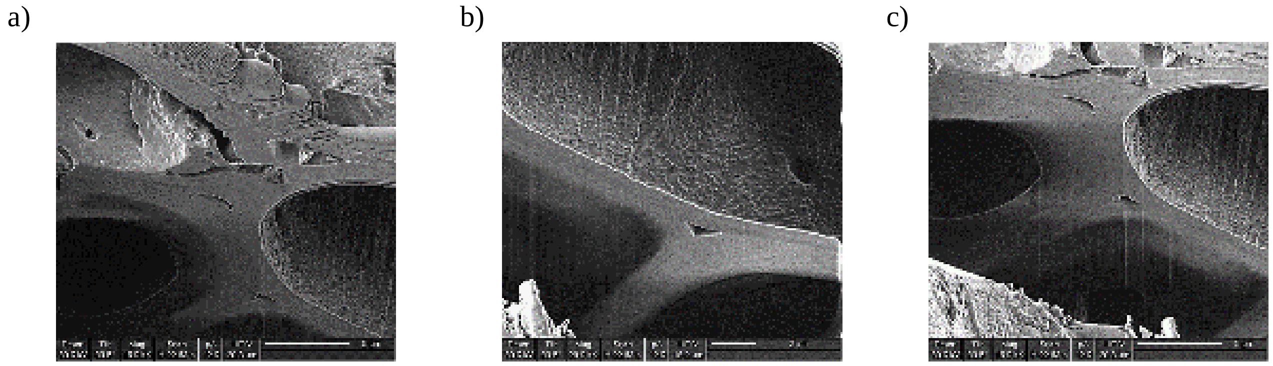

Figure 7 Detailed views of darker zones around the cell walls in Figure 6.

With the aim of analysing the elemental composition of the dark areas imaged with FIB in Fig. 6 and 7, EDX analysis was undertaken. A specific area (within the red rectangle in Fig. 6b) was analysed. Results of the EDX analysis are shown in Fig. 8. The high concentration of Si in Fig. 8d confirm the results of FIB observations. This suggests that most of the amorphous silica polymerized in the outer part section of Guadua bamboo (Fig. 3) is concentrated within the cell walls, and that effective reaction of silica with lime will require exposure of the cell wall structure.

Limeboo samples were also imaged using SEM and subjected to EDX analysis. Figure 9a shows a SEM cross section of Guadua near the cortex. This sample was extracted from the Limeboo sample made with dolomitic lime. Figure 9b to 9f show the elemental distribution map of carbon (C), oxygen (O), silicon (Si), calcium (Ca) and magnesium (Mg) for the same SEM image. The EDX maps suggest a high concentration of Ca, Si and O inside the lumen whereas the surrounding walls are rich in C. Mg appears homogeneously distributed in the whole section. This result would be consistent with the formation of a C-S-H phases inside the cell as a consequence of the reaction between lime and the amorphous silica content of Guadua. However further work which is beyond the scope of this paper would be required to confirm this hypothesis.

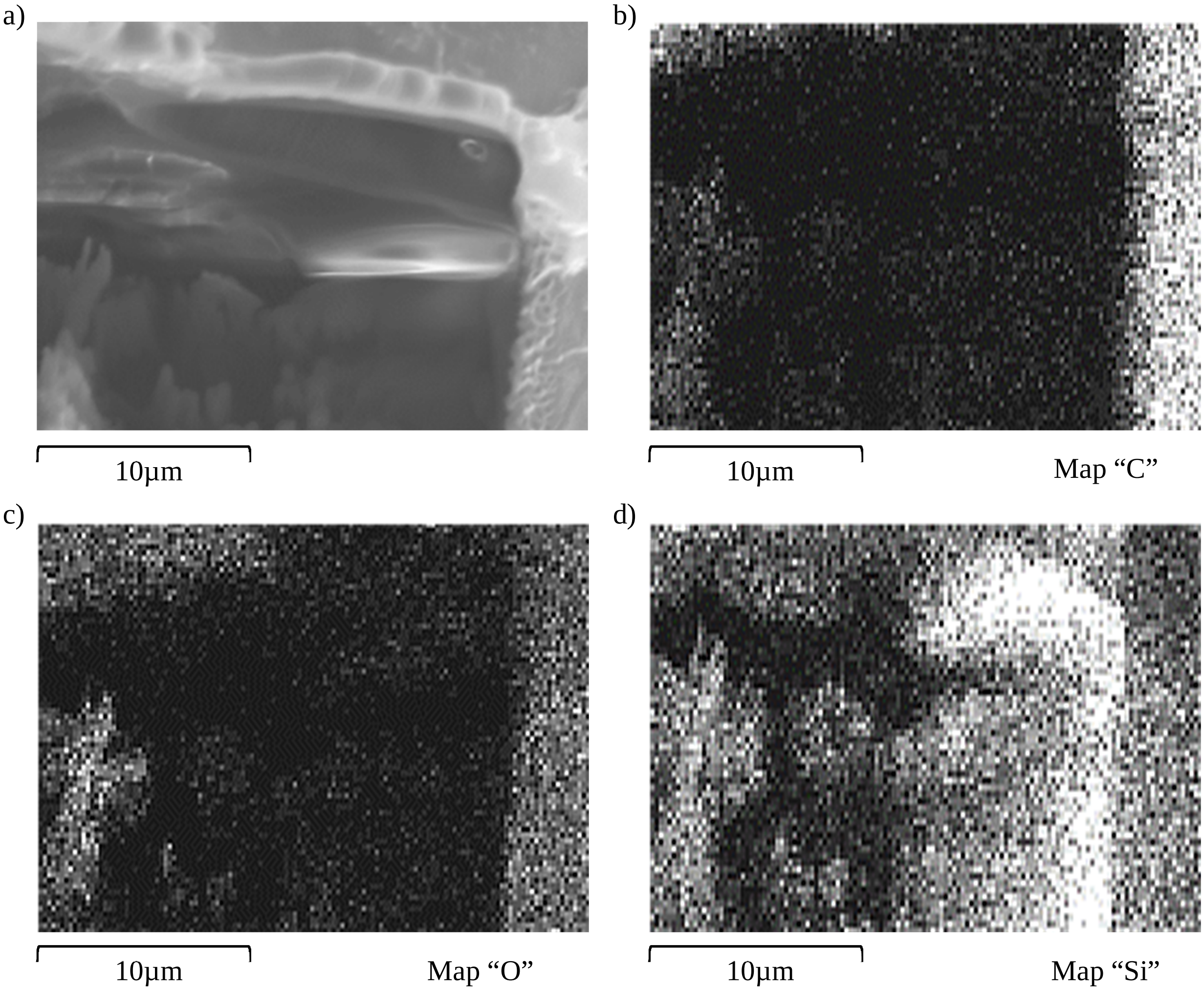

Figure 8 a) SEM image of one of the cell walls in figure 4. b)-(d) maps of Carbon, Oxygen and Silicon for the same cell

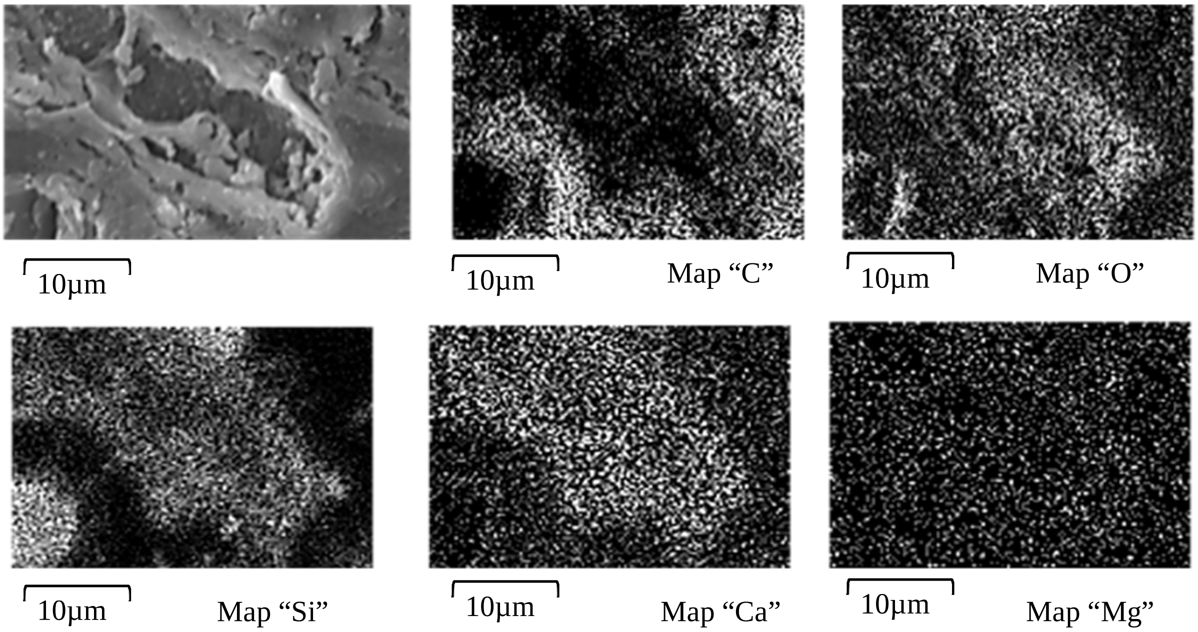

Figure 9Elemental analysis of a section of Limeboo DL85-S2 pre-treated with a saturated solution of Ca(OH)2. a) SEM image. b) to g) EDX maps of carbon, oxygen. silicon, calcium and magnesium in the same imaged section.

Conclusions

This paper presents the results of ongoing research and represents a proof of concept (which requires further investigation) on the use of cold processes for the exploitation of the amorphous silica contained in bamboo as a method to improve the bonding between lime and bamboo. Although at microscopic level, the conducted tests proved the feasibility of using lime for renders in '*bahareque*' systems, at macroscopic scale improvements are suggested.

Despite observing deposition of calcium within epidermal cells (some of which showed a high content of Si), Limeboo samples displayed poor adhesion between the lime mortar and bamboo-Guadua. With the aim of improving this interface, pre-treatment options that break down the cell structure need to be sought. This will allow lime to flow inside the cell where, as we demonstrated, it may react with the amorphous silica forming a CSH type phase.

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