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Adobe wall biodeterioration by the *Centris muralis* Burmeister bee (Insecta: Hymenoptera: Apidae) in a valuable colonial site, the Capayán ruins (La Rioja, Argentina)

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ABSTRACT

Historic earthen buildings in central western Argentina constitute a valuable resource for studies of recent material culture. Without adequate care and maintenance, these types of buildings are susceptible to damage by physical or biological processes. A specific type of damage was identified in earthen walls of the Capayán ruins, in La Rioja, Argentina. The aim of the present study was to determine the cause of this damage and understand the biodeterioration process. The wall selected for this study exhibited massive erosion in zones used by bees for nesting. These zones presented easily distinguishable patches of coarse appearance on the wall surface. A high density of cavities as a result of the removal of the cells (708 cavities m^{-2}, SD < 5%) was observed. The causal agent was identified as the bee *Centris muralis* Burmeister. The weight of the material lost from the wall due to biodeterioration was estimated at 729 kg of earth. Erosion in the attacked parts reduced the thickness of the adobe wall ca. 7 cm compared to parts without nests. This study demonstrates that earthen walls are subject not only to damage by weathering, but also to biodeterioration.

1. Introduction

Historic building resources, which help tell the story of peoples, are part of the evidence of past human occupations. The materials used for these buildings exhibit a wide range of resistances/fragilities when exposed to atmospheric weathering, being earthen structures particularly labile to erosion by rainfall and wind. In Argentina's La Rioja province, earth was the most important building material used in the 18th to 19th centuries. Presumably, Capayán ruins constitute a settlement built in the Argentinean colonial period (De la Vega Díaz, 1994). This settlement is composed of a group of historic earthen buildings that were built by using two construction techniques: adobe masonry and rammed earth. Adobe masonry was the predominant technique used for building the walls in Capayán ruins. This technique consists of fixing the adobe sun-baked bricks by a complex and glutinous earthen material called mortar; identical material was used in the plaster that covers the walls. Nowadays, the Capayán ruins constitute a highly valuable example of local architecture because of their patrimonial, aesthetic, historical, and touristic aspects. Moreover, the diversity of building morphologies as well as the preservation state of this settlement should allow for more complete studies focused on the culture of the early Spanish occupation of the current arid lands of central western Argentina. These resources from material culture are gradually disappearing because of the lack of awareness of their patrimonial value, which in turn could explain the inadequate protective legislation.

In addition, although buildings persist for long periods, continuous physical changes caused by environmental conditions lead to significant damage or loss of archeological earthen structures; water, salt attack, and earthquakes are the main environmental factors (Chiari, 1985; Tolles et al., 1996; Fujii et al., 2009). Deterioration caused by attacks by organisms has also been identified in serious damage to historic earthen buildings (Matero, 1999; Fodde, 2007a; Ridout, 2008). Thus, experimental programs aimed at developing new materials and techniques for use in conservation of historic earthen buildings are becoming increasingly important option (Degirmenci and Baradan, 2005; Fodde, 2007b; Elert et al., 2008; Martínez-Camacho et al., 2008).

These ruins are situated in the northern area of the Monte desert. The climate is subtropical, warm temperate, with a mean annual temperature of 15 °C and annual rainfall ranging from 80 to

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200 mm. The biogeographical province of Monte is defined as a xeric biome according to its vegetation and physiognomy (Roig, 1998; Roig-Juñent et al., 2001). The area can best be described as a shrub steppe. The characteristic endemic flora is represented mainly by the family Zygophyllaceae (*Larrea*, *Bulnesia*, and *Plectocarpa*). Flowering has been observed to be restricted to spring-summer (September to April). In addition, some species present two blooming periods; the most important of these species, because of their predominance in this arid ecosystem, are *Larrea divaricata* and *Bulnesia retama* (Michelette and Camargo, 2000). These plants provide a source of wildflowers on which local entomofauna feed.

Most of the studies have been focused on the biodeterioration of valuable wood objects damaged by fungi and bacteria (Blanchette, 2000; Huisman et al., 2008; Fazio et al., 2010). Fungi and bacteria are difficult to detect but, due to their saprobic nutritional mode, they contribute significantly to the deterioration of wooden objects, causing aesthetic and structural damage of cultural importance. Biodeterioration of monuments and buildings by plants and lichens acting as the biodeteriogenic agents has also been reported previously (Mishra et al., 1995; Lisci et al., 2003). By contrast, insects have not been reported as important deterioration agents. In fact, reports dealing with this topic are significantly scant, with termites being the most treated topic (Alves da Silva et al., 2007; Clausen and Yang, 2007; Verma et al., 2009).

The present work was undertaken to better understand the biodeterioration process and to determine what part bees have played in the deterioration observed in the earthen walls of Capayán ruins, a valuable historic site in La Rioja, Argentina.

2. Materials and methods

2.1. Study site and sampling

The site investigated in this study was located in Famatina Department, in the valley of Antinaco-Los Colorados (La Rioja, northwest Argentina, 29° 03′ south lat. 67° 26′ west long.), 10 km from Chilecito at 1033 m above sea level. Only one wall was selected for study; the selection was based on this wall's severe damage, the possibility for sampling without causing significant damage, and the fact that this wall was within reach. The adobe wall and its deteriorated area were visually inspected and exhaustively photographed using a Canon EOS 350D camera (Canon Inc., Tokyo, Japan). Samples, approximately 2.50 kg each (approx. 10 × 10 × 15 cm), were taken from detached material consisting of three pieces of deteriorated and non-deteriorated adobe bricks.

2.2. Analytical determinations

Granulometry was determined by the hydrometer method (Bouyoucos, 1936) using 100 g of adobe brick. Fibre content was determined by the flotation method. Briefly, 100 g of adobe brick was dried at 50 °C until constant weight was reached. Dried pieces were disintegrated in a mortar and sieved (60-mesh), the retained fraction was transferred to 1 L of distilled water, and the floating fibres were collected, dried overnight, and weighed. Three independent determinations (unless otherwise stated) were conducted; mean values and standard deviations (SD) were calculated. Units were defined as percentages (w/w). For estimating adobe brick density, samples (8–40 g each) were weighed after drying overnight or after constant weight. Then, samples were waterproof painted with lacquer and their volume was estimated by displacement (Archimedes principle); since the displaced liquid was distilled water the weight of the displaced liquid (in grams) was equivalent to the volume (in cubic centimeters). The density of the samples was estimated according to the equation:

$$\text{Density}\left(\text{g cm}^{-3}\right) = \text{dry weight of sample}(\text{g})/\text{volume of displaced distilled water}\left(\text{cm}^{3}\right)$$

Deteriorated and non-deteriorated areas were estimated by using digital photographs previously converted onto silhouette by redrawing (AutoCAD, 2005, Autodesk Inc.). Thinning in the biodeteriorated zone of the adobe wall was measured in 25 randomly chosen points. The non-biodeteriorated zone of the wall was taken as reference.

The volume of detached material was estimated according to the equation:

$$\text{Volume}\left(\text{cm}^{3}\right) = \text{depth by detached material}(\text{cm}) \times \text{surface biodeteriorated}\left(\text{cm}^{2}\right)$$

Then, total weight of the withdrawn earthen material was estimated according to the equation:

$$\text{Total weight}(\text{g}) = \text{volume}\left(\text{cm}^{3}\right) \times \text{density}\left(\text{g cm}^{-3}\right)$$

Ten independent determinations (unless otherwise stated) were conducted; mean values and SD were calculated.

2.3. Nest analyses

For nest analyses, the study was conducted in two stages. The first step was to determine distribution pattern, density, and orientation of the nests in the adobe samples. In the second stage, the cell cavities were cleaned to measure the length and width. The sediments from the cell cavities were examined to determine the presence of pollen and fecal deposits. Non-emerged adults and larvae were used for taxonomical identification. For estimating cell density only those exposed on the wall surface were considered. For estimating volume the cells were removed and impermeabilized; the methodology was that described in Section 2.2 for estimating density. Ten independent determinations were conducted, and mean values and SD were calculated.

2.4. Ultrastructural analyses

Samples from deteriorated and non-deteriorated adobe brick were impregnated with Araldite epoxy resin (Distraltec, Buenos Aires). Then, thin sections were prepared according to the technique described by Jongerius and Heintzberger (1975) mounted, and observed under the light microscope (LM). For scanning electron microscope (SEM) observation, pieces of deteriorated and non-deteriorated adobe bricks were dried at 80 °C overnight. The particles were taken with a V-shaped-end microspatula, gold coated, and mounted for examination under SEM (SEM EDS, Inca Energy, Oxford Instruments scanning electron microscope with field emission gun [FEG] Zeiss DSM 982 Gemini secondary electron in-lens detector). The samples were taken from three zones determined as distances from the inner cell layer: 0–1 mm, 1–3 mm, and 3 mm onward.

2.5. Palynological analysis

Palynological analyses of samples from cell contents ($N = 25$) were used to determine the collecting habits of the bees. The cell sediments were treated with potassium hydroxide solution (KHO) in a double boiler. The deflocculant properties of KOH (Faegri and Iversen, 1975) allow the successful separation of the pollen adhered to cell sediments. An aliquot of the sample of the polliniferous material was mounted in glycerin on a slide and stained with fuchsin, and total pollen was counted. For the taxonomic recognition, the pollen reference collection of specimens collected around the study area was used after preparing it with the technique described above.

3. Results

3.1. Adobe wall characterization

The adobe wall and its deteriorated area was consistently observed, measured, photographed, and represented graphically (Fig. 1). It consisted of adobe sun-baked bricks of 10 × 20 × 40 cm bound to each other using earthen mortar joints 3 cm thick. The wall consisted of 28 adobe courses with alternative courses of headers and stretchers (English bond) resulting in a 40-cm-thick and 325-cm-high wall. Patches of plaster (2 cm thick) in the first courses of the adobe wall were observed. Distribution in granulometry was: 24% sand, 64% silt, and 12% clay. In biodeteriorated adobe bricks, the fiber content was 1.31 ± 0.19% (mean ± SD) and the density was estimated to be 1.62 ± 0.15 g cm^{-3} (mean ± SD), whereas in non-biodeteriorated adobe bricks, fiber content was 3.08 ± 0.28% (mean ± SD) and density 1.38 ± 0.12 g cm^{-3} (mean ± SD). The fiber content in earthen mortar was undetectable. The eroded zones exhibited high density of cavities on the surface as a result of removal of the cells (708 cavities m^{-2}, SD < 5%, with greater concentration toward earthen mortar joints), which resulted in 9.38 kg of material removed by bee activity. The estimated biodeteriorated area was 5.52 m^2 (Fig. 1c, shaded). The weight of the material lost from this wall due to biodeterioration (and mechanically eroded by water and wind) was 729 kg, equivalent to 0.45 m^3. Erosion in the attacked parts reduced the thickness of the adobe wall ca. 7 cm compared to parts without nests (Fig. 2). Interestingly, we observed that the 11 lower adobe courses did not exhibit the same density of cavities observed in the higher courses. Low density of nests was observed on the joint of non-biodeteriorated zones, but no cells were observed on adobe bricks.

3.2. Nest characterization

The nest cells were usually found to be oriented vertically (10° with respect to the vertical axes) or somewhat slanting (75° with respect to the vertical axes) and up to 12 cm into the wall (Fig. 3). The cells were separable from the substrate with difficulty and not completely. The cavities of the cleaned cells (N = 10) were 20–22 mm in length and 12–14 mm in diameter. The volume of each cell was 1.49 ± 0.13 cm^3 (mean, SD). The non-emerged adults and larvae with varying states of development found within the cells inserted into the walls were identified as *Centris muralis*.

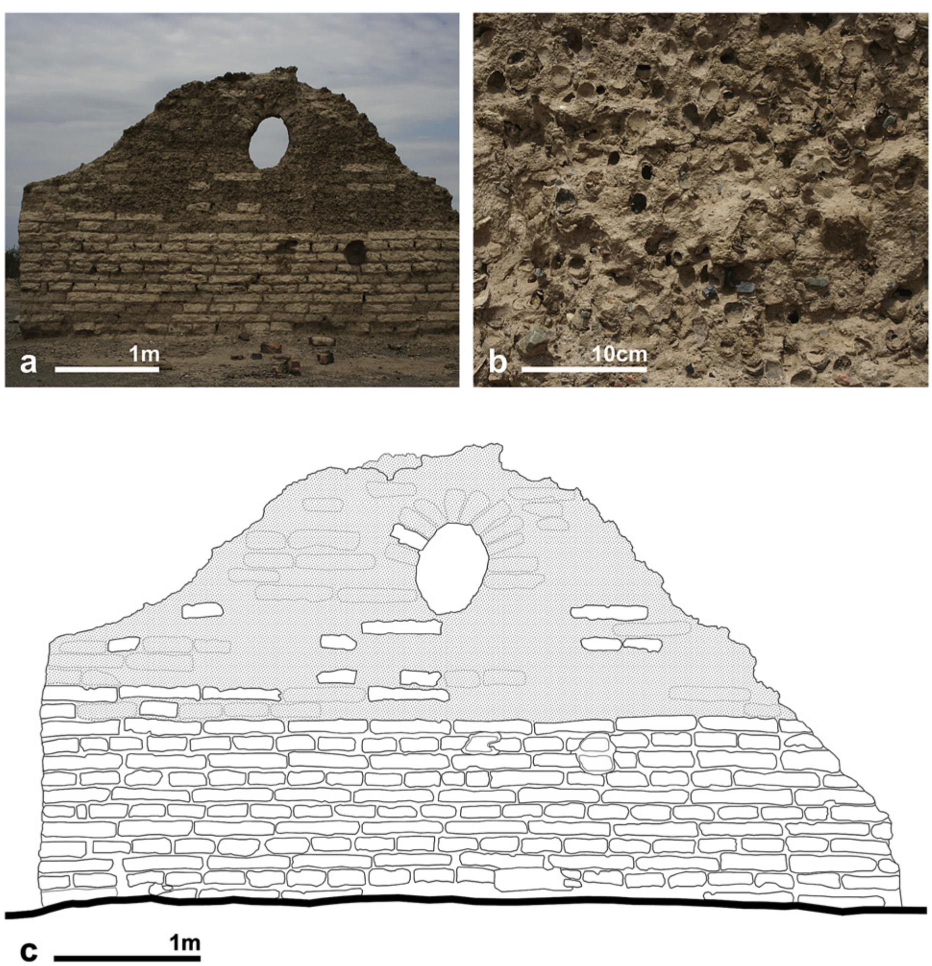

Fig. 1. (a) General view of an adobe wall from the Capayán ruins showing damage by biodeterioration. (b) Detail of superficial biodeteriorated area. Patches of coarse appearance due to the high density of cavities are easily distinguishable. (c) Graphical representation of the adobe wall, with the biodeteriorated area in gray.

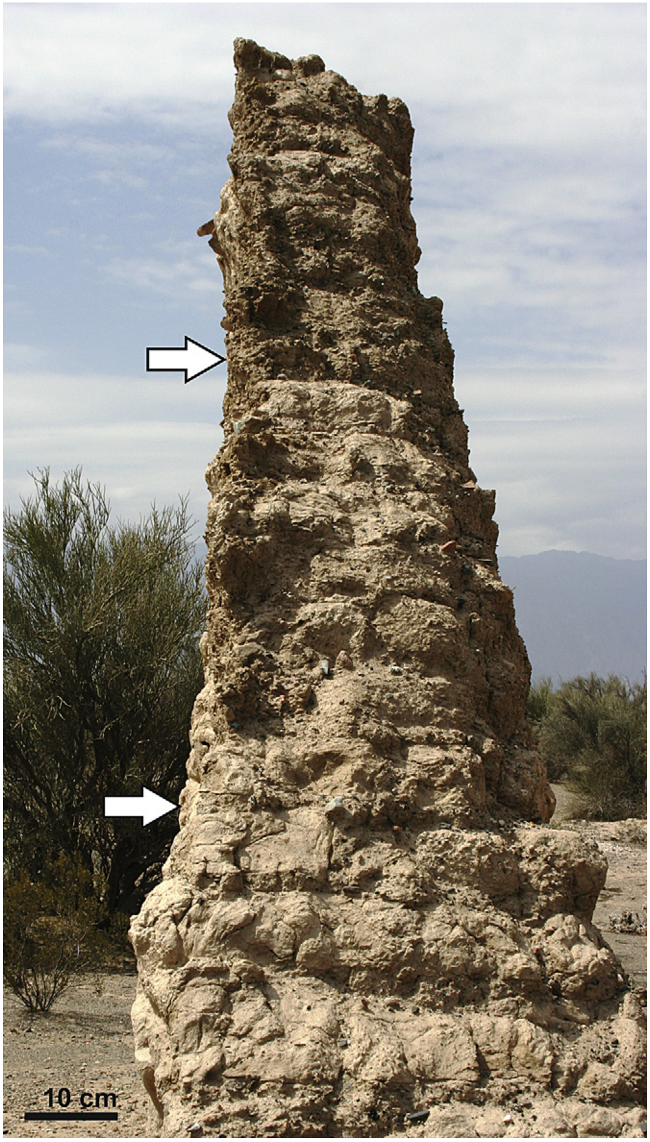

Fig. 2. Adobe wall profile. Arrows indicate biodeteriorated (upper arrow) and non-biodeteriorated (lower arrow) zones.

Fig. 3. Arrangement of cells and cavities in the wall.

In zones that exhibited lower density of nests, it was possible to study cell arrangement. Bees completed a nest with one cell; there was a separate nest for each cell or two cells. In some cases, two cells defining a linear series pattern were present. The cell walls were harder than the adobe matrix even where the substrate was comparatively firm. This hard material was probably made of compacted soil particles cemented with a hardening material and probably waterproofed by bee secretions (outer layer). The inner surface of the cell was smooth and lined with a thin, semi-transparent shiny waxy material on the entire surface. Then this species spun a cocoon that formed the inner cell surface with the waxy material adhered to it (inner layer). The cells were found to be reoccupied by other specimens of *C. muralis*. Some cells contained doubled thin waxy layers characteristic of *C. muralis*. Because of the degree of erosion, many of the cells studied in the Capayán ruins were exposed on the surface of the wall and thus the tunnel entrance to the nests could not be studied.

3.3. Analysis of light micrographs

Thin sections of biodeteriorated adobe brick samples mounted and observed under light microscopy exhibited two layers – an inner layer of organic material and an outer layer approximately 0.7 mm thick, consisting mainly of clay, silt, and some fine sand grains (Fig. 4). These particles adhered to each other by a type of cementitious material probably secreted by the bee. No alterations were observed beyond the outer layer structure.

3.4. Scanning electron micrographs

Scanning electron micrographs illustrate the effect of nesting on the adobe brick structure. In the 0–1 mm zone, a smooth and continuous surface as well as spores was observed (Fig. 5a). The material from zones 1–3 mm and 3 mm onward (Fig. 5b and c, respectively) exhibited high quantities of clay crystals.

3.5. Palynological analysis

Pollen from *Larrea* spp. (*Larrea cuneifolia* [72%], *L. divaricata* [24%], and other minor pollen source species) was observed in high proportions mixed with the cell sediments, thus suggesting that

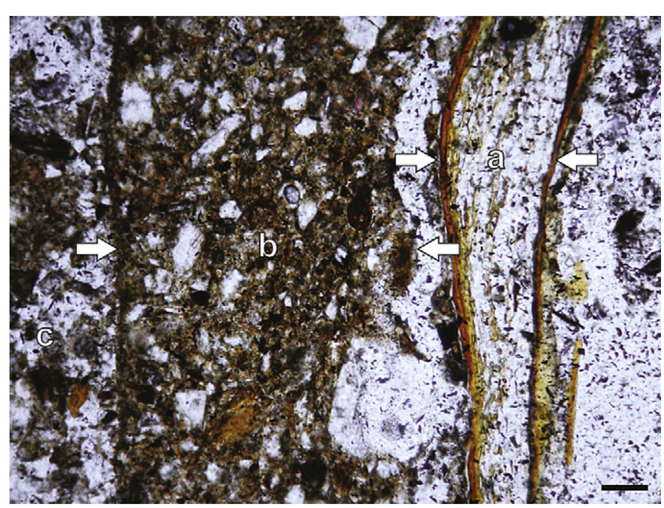

Fig. 4. Light microscope micrographs illustrating cell walls exhibiting the inner layers of organic material (a) and the layer of 0.7 mm thick consisting mainly of silt, clay and fine sand grains in low rate (b). Beyond the thick layer there is no material alteration due to nesting activity (c).

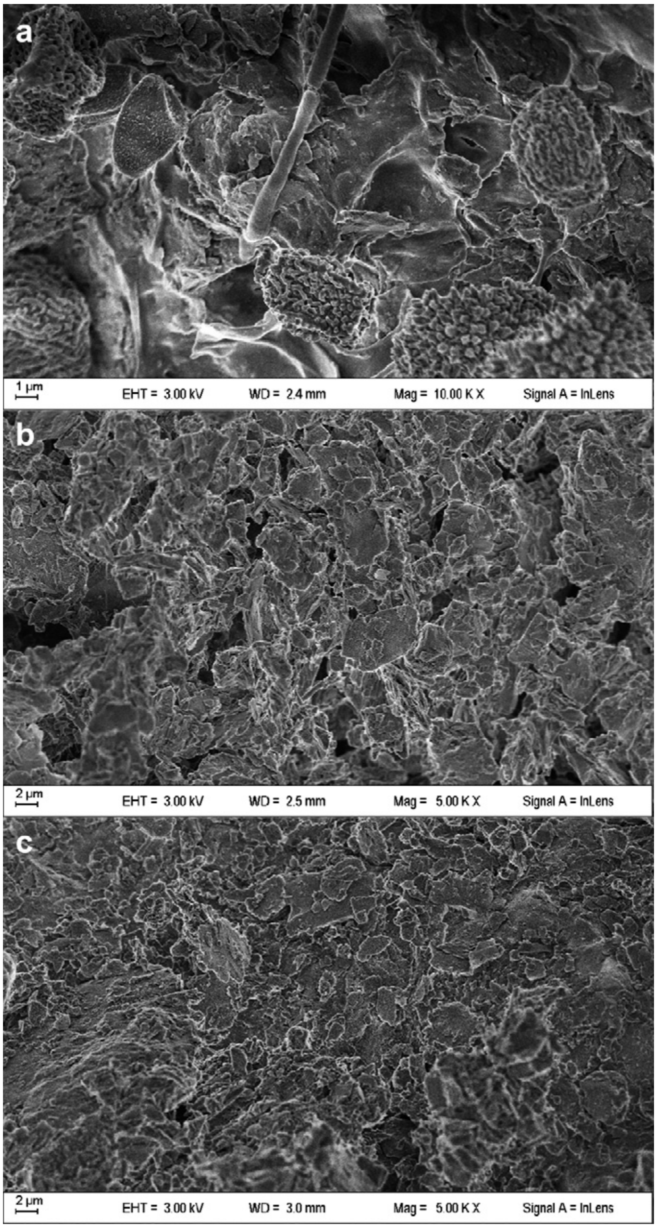

Fig. 5. SEM micrographs illustrating a biodeteriorated adobe brick. Samples were taken from: (a) The inner limit of the cavity up to a distance of 1 mm, (b) 1 mm from the inner limit up to a distance of 3 mm, and (c) Further than 3 mm. Note the presence of spores in (a) and abundant clay crystals in (b) and (c).

these plants provided the main source of wildflowers. Several unidentified spores were also found in the cell sediments.

4. Discussion

Two factors were probably crucial for the walls of the Capayán ruins to become the preferred suitable nesting habitat for *C. muralis*: the availability of forage in close proximity to the nests and the large homogeneous surface to which the structure created a habitat that was attractive as nesting site.

Inside the nests, abundant pollen from *L. cuneifolia* and *L. divaricata* was found, suggesting that these plants provided the main source of wildflowers on which bees could feed. The preference of *C. muralis* for *L. divaricata* was demonstrated in a previous report (Michelette and Camargo, 2000). The high amount of pollen of *L. cuneifolia* and *L. divaricata* suggests that an important blossom occurred at that time (Aguiar and Gaglialone, 2003). The high density of *C. muralis* was probably due to the high availability of resources, and it is possible that at least part of the materials used for nest construction were collected from *Larrea* spp.

Other species allied with *C. muralis*, such as *Centris tricolor*, *Centris brethesi*, *Centris nigripes*, *Centris cineraria*, *Centris nigerrima*, *Centris autrani*, and *Centris furcata*, have also been observed nesting and causing deterioration in building walls (Jörgensen,1909; 1912; Janvier, 1926; 1955). To our knowledge, only two reports (Jörgensen, 1909; 1912) have dealt with the nesting biology of *C. muralis*. However, these studies were incomplete and consisted only of preliminary observations and descriptions of *C. muralis*. In other studies, species of the genus *Centris* were frequently observed nesting on earth banks (Michener, 2007). In the present work, the high density of nests was probably due to both the high density of *L. cuneifolia* and *L. divaricata* and the presence of a suitable large surface for nesting. The proximity among nests and clustered distribution of foraging flowers have been proposed to be related (Aguiar and Gaglialone, 2003), but the extraordinarily high density of *C. muralis* nests observed in the adobe walls studied has not been reported previously.

It is probable that the outer layer was constructed by particles adhered to one another by a cementitious material deposited by the bee. This idea was reinforced after observing that the SEM photographs of the outer layer exhibited a smooth surface and a total lack of clay crystals.

The erosive effect of *C. muralis* is two-fold: (1) The insects actively remove material from adobes when digging deep cavities to nest, and (2) cavities weaken the adobe structure and some parts collapse as a result of pulling out. After nest construction, wind, and more likely rain, reinforces the mechanical action of nesting. In addition, the cementitious material of the outer layer, along with the waterproof inner layer, prevents the penetration of water. For this reason, the erosive effect of water around the cells causes their detachment from the wall. The continuous process of cell detachment results in the current severely eroded condition. Thus, climatic factors (e.g., sporadic but intense rains) are certainly partly responsible for such collapses but they would probably not occur if the wall were not weakened by hundreds of cavities. Therefore, it could be assumed that the ultimate factor accounting for collapses is the mining activity by *C. muralis*. Erosion in the attacked parts thinned the adobe wall about 7 cm compared to parts without nests.

The composition in the adobe matrix was probably determinative in the substrate selected by *C. muralis* for nesting. This composition in the 11 lower adobe courses was presumably different from that in the higher adobe courses, where no cells were observed on adobe bricks. This idea could be reinforced upon observing the absence of those cavities in a few adobe bricks in the higher courses in contrast to the all other adobe bricks attacked in the same zone (Fig. 2).

The highest fiber content was observed in non-biodeteriorated adobe bricks, while the biodeteriorated adobe bricks contained less than half the fiber of the non-biodeteriorated. The addition of different plant fibers is common in adobe matrix to improve compressive and tensile strength (Yetgin et al., 2008), which suggests that these variables may contribute to the differential patterns of bee attack exhibited by different adobe bricks and earthen mortar.

The first historic adobe buildings in La Rioja are invaluable remains of Spanish-Indian contact in South America. Moreover, these buildings represent an architectural example of the times when La Rioja was populated by indigenous people, the Spanish, and descendants of the Spanish in America (criollos), who, at the direction of the first Hispanic colonizers, constructed most of these buildings. Earthen buildings of the colonial period in La Rioja are scant, being the earliest historic buildings and the most vulnerable structures. Thus, surviving historic earthen architectural structures in La Rioja are among the most historically and culturally significant structures. In this study, we have demonstrated that they are subject not only to damage by weathering, but also by biodeterioration.

Adobe wall biodeterioration by *C. muralis* is not sudden. This is a long process, the harmful effect of which is seen in the high density of cavities. Because of the abandoned state of these ruins, the structure and stability of the constructions is compromised.

We consider that it is possible to prevent this biodeterioration process with minimum maintenance by obstructing the orifices made by the bees and using natural or artificial repellents and deterrents.

However, when the presence of a significant number of cells threatens the stability of the entire wall, our recommendation is to remove the nests and clean the affected area to carry out consolidation tasks. In these cases it is necessary to prevent the irregularities of the affected areas that remain outdoors, as these irregularities and outdoor exposed nests are associated with accelerated physical deterioration. Similar criteria have been applied for the conservation of earthen structures in Sardinia, Italy (Fodde, 2007c). The results of this study contribute to the knowledge of biodeterioration as a factor in various deterioration processes that affect historic earthen buildings. The ultimate goal should be the use of all existing knowledge to better safeguard these invaluable Argentinean buildings.

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