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Exploring the potential of locally sourced biopolymers to stabilize lateritic earthen construction.

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Abstract. French Guiana needs affordable local building materials to cope with high population growth and the high cost of imported cement. Earthen construction could represent a local, cost-effective, and ecologically friendly alternative. However, earth materials are highly vulnerable to water, which represents a significant concern in humid tropical climates. Although hydraulic binders effectively stabilize earthen construction, they increase economic and environmental costs. Biopolymers could offer a sustainable alternative, but their effectiveness varies depending on the nature of the soil. French Guiana has highly weathered soils with a high iron and aluminum oxide content, and it remains unknown if biopolymers could be used to stabilize this type of soils. This study had three objectives. First, assess some soil diversity by examining the chemical and mineralogical composition of 17 soils. Second, identify locally available biopolymers that can be extracted from waste or agricultural by-products. Finally, examine the interactions between two different soils and tannin, a well characterized biopolymer used ancestrally to stabilize the lateritic construction.

Results revealed that the soils were predominantly composed of SiO_2 , Al_2O_3 and Fe_2O_3 in different proportions and infrared spectroscopy allowed the identification of three different minerals: kaolinite (clay), gibbsite (aluminum oxide) and goethite (iron oxide). Five local by-products were identified for the extraction of biopolymers for earth stabilization: tannin, starch, mucilage, cow dung and chitosan. Additionally, a complex reaction between tannin and iron oxide was observed in the iron-rich soil, highlighting the importance of selecting a soil adapted to the biopolymer. Altogether, this study gives a first insight into the potential of bio-stabilized earth construction in French Guiana, highlighting the need for further research to determine how the five locally identified biopolymers improve the water-resistance of earthen construction.

Keywords: Earthen construction, laterite, biopolymer, tannins.

1 Introduction

French Guiana is located between Suriname and Brazil in the north of South America. With 96% of its territory covered by forests, the majority of the population lives along

the coast and on riverfronts. The rapid population growth in French Guiana has led to an increasing demand for affordable and locally-sourced building materials. Earthen construction, comprised mainly of locally-sourced soil and additives, presents an appealing alternative owing to its abundance, low ecological footprint and recyclability [1–3]. However, without stabilization, earthen materials are highly susceptible to water ingress, preventing their use in humid tropical regions [4,5].

Hydraulic binders, such as Portland cement or hydraulic lime, are commonly used to improve earthen construction's durability and mechanical performance. For instance, a local company offers a cement-stabilized compressed earth brick (SCEB) suitable for load-bearing walls. However, the absence of limestone quarries in French Guiana requires the import of cementitious materials, increasing the economic and environmental cost of the cement-stabilized materials. Furthermore, by reducing the soil's moisture buffering capacity and vapor permeability, hydraulic binders have a detrimental effect on the hygrothermal properties of earthen materials [4,6,7]. The need to replace hydraulic binders in construction has led to a growing interest in using biopolymers to stabilize earthen construction [8–18].

A biopolymer is a naturally occurring polymer that can be used to increase the strength and water resistance of earthen materials by modifying the soil's microstructure. Biopolymer stabilization is achieved through physical processes such as pore-filling and macro pore size reduction and physicochemical interactions such as ionic interactions, hydrogen bonding or cation exchange. An extensive range of biopolymers derived from various sources such as animals (cow dung, chitosan, ovalbumin, casein), plants (tannin, lignin, mucilage), seaweeds (alginate, carrageenan) or microbes (xanthan gum) has been used to enhance the durability of earthen construction. As highlighted in various studies the suitability of the biopolymer largely depends on the interaction between the biopolymer and the soil, in particular with the mineral clay fraction. The soils of French Guiana are highly weathered residual tropical soils with high amounts of iron and aluminum oxides and hydroxides, commonly denominated as lateritic soils. Iron and aluminum oxides strengthen soil structure by cementing clay particles together, forming strong aggregates [24–26]. However, the effect of biopolymers on laterite soils and their potential use as stabilizers remain understudied.

This study first examined the chemical composition of 17 soils collected on lateritic quarries on the French Guiana coast. Subsequently, the utilization of locally-extractable biopolymers for earthen stabilization was defined and analyzed. To ensure their sustainability, the selection of biopolymers necessitates meticulous consideration. Despite the generally low quantity of biopolymer required for stabilization, the economic and environmental costs of biopolymer stabilization can be substantial due to the chemical processing and thermal treatment involved in biopolymer extraction. Consequently, a more promising solution is to explore the use of locally-sourced waste or by-products as sources of bio-stabilizers. To evaluate the influence of soil properties on biopolymer stabilization, we conducted preliminary tests using tannin, a well-known biopolymer, with two different types of soil prior to testing local biopolymers. This research may contribute to developing sustainable earthen construction in tropical regions.

2 Materials and methods

2.1 Soils

A total of seventeen soil samples were collected from seven distinct quarries located on the coast of French Guiana (**Fig. 1**). The soil samples were chosen to be representative of the various types of soils present in each quarry, considering differences in texture and color that could be observed visually. The soil samples were given names based on the first letter of the nearest city, with A representing Awala, C for Cayenne, M for Mana, K for Kourou, S for Sinamary, SLM for Saint-Laurent-du-Maroni and T for Tonate, with numbers added to differentiate samples taken from a single quarry.



Fig. 1. Localization of the seven quarries along the French Guiana coast

2.2 Soil chemical and mineral composition

The chemical composition of the soils was evaluated by Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES) with the Loss On Ignition (L.O.I.) performed at 1000 °C on crushed and 80 µm sieved samples. The mineralogical composition was assessed on the same samples by Attenuated Total Reflectance-Fourier Transformed Infrared (ATR-FTIR) performed in the range of 4000-400 cm⁻¹ with a 4 cm⁻¹ resolution through 128 scans.

2.3 Interaction tannin-soil

A commercial tannin extract from chestnut trees was used to evaluate chemical reactions between tannin and two different local soil. Soils were chosen based on their different iron ratios. The soils were sieved at 2 mm, mixed with 3% tannin by mass, and moistened at the same water content: W=27%. The mixture was then molded into disc-shaped samples (diameter=6 cm, height=1.5 cm) and oven dried at 40°C until their mass stabilized. A sample was collected from the middle of the disc, then crushed and sieved

at 80 μ m. Finally, the interaction between tannin and soil was investigated using ATR-FTIR performed in the range of 4000-400 cm^{-1} with a 4 cm^{-1} resolution through 128 scans.

3 Results and discussion

3.1 Soil chemical and mineral characterization

Chemical composition and loss on ignition were measured by ICP-OES on crushed samples (< 80 μ m) and summarized in Table 1. These results were consistent with the soil's chemical composition and typical for lateritic soils. To conclude, the principal difference between the different soils was their iron and aluminum oxide ratio.

Table 1. The SiO_2 (28.7–75.4%), Al_2O_3 (12.1–36.5%), Fe_2O_3 (2.8–24%) and TiO_2 (0.7–4.51%) contents were the highest among the principal oxides, a typical result for lateritic soils [27,28]. The Fe_2O_3 , SiO_2 and Al_2O_3 ternary diagram [29] was used to categorize 17 soils into 8 laterite, 6 bauxitic kaolinite and 3 kaolinite types (**Fig. 2**). Interestingly, soils present in the same quarry could present a significant variability in their composition. For instance, the Mana quarry had soils classified as kaolinite or bauxitic kaolinite and the Kourou quarry had soils classified as laterite and bauxitic kaolinite.

The ATR-FTIR analysis of the 17 soils (**Fig. 3**) revealed the presence of three minerals: kaolinite ($\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$), a phyllosilicate [30], gibbsite ($\text{Al}(\text{OH})_3$), an aluminum oxide [31,32] and goethite ($\text{FeO}(\text{OH})$), an iron oxyhydroxide [31,33]. These results were consistent with the soil's chemical composition and typical for lateritic soils. To conclude, the principal difference between the different soils was their iron and aluminum oxide ratio.

Table 1. Major oxide composition of the 17 soils samples

Chemical analysis (%) measured by ICP-OES												
Soil	SiO_2	Al_2O_3	Fe_2O_3	TiO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	L.O.I	total
A	38,61	33,74	9,61	1,90		0,04	0,07		0,10		15,18	99,24
C1	47,90	31,95	4,96	0,72	0,10	0,15	0,06		0,39	0,10	13,77	100,1
C2	46,76	33,57	3,82	0,87	0,024	0,26	0,09		0,97		13,45	99,82
K1	43,08	36,52	3,23	1,97		0,05	0,06		0,16		14,19	99,26
K2	30,70	30,28	19,55	3,01	0,057		0,04		0,07		15,57	99,27
K3	38,97	33,85	10,33	1,34	0,050		0,07		0,22		14,67	99,49
K4	28,72	26,99	24,07	4,51	0,11					0,12	14,42	98,94
M1	42,27	33,82	6,59	2,18		0,07	0,07		0,37		13,84	99,20
M2	61,35	14,56	14,42	1,22		0,05	0,06		0,14		7,56	99,37
M3	75,36	12,14	6,36	1,35	0,017	0,06	0,04		0,14		5,28	100,7
M4	64,91	15,65	9,98	1,58	0,022	0,08	0,05		0,17		6,76	99,19
S1	34,27	34,67	12,67	1,88		0,06			0,17		15,12	98,84
S2	39,76	27,62	16,60	2,37	0,019	0,18	0,03	0,04	0,17		11,79	98,56
S3	36,06	29,23	19,20	2,03	0,083	0,82	0,09	0,26	0,26		11,17	99,18
SLM1	36,89	33,43	12,77	1,42		0,03	0,06		0,24		15,46	100,3
SLM2	40,59	34,90	7,61	0,86		0,05	0,05	0,03	0,70		14,41	99,21
T	55,83	24,51	2,82	0,88		0,63	0,26	0,29	1,74		12,14	99,10

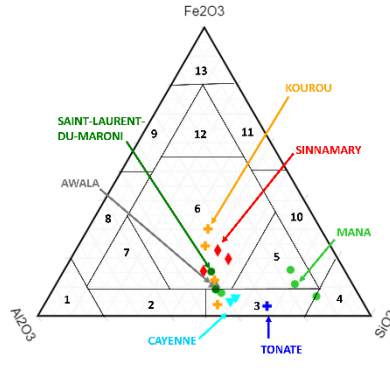


Fig. 2. Fe_2O_3 , SiO_2 , Al_2O_3 ternary diagram of the 17 soil samples [29] - 1: bauxite; 2: kaolinitic bauxite; 3: bauxitic kaolinite; 4: kaolinite; 5:kaolinite; 6: laterite; 7: bauxite; 8: ferritic bauxite; 9: bauxite ferrite; 10: ferritic kaolinite; 11:kaolinitic ferrite; 12: ferritic laterite; 13: ferrite;

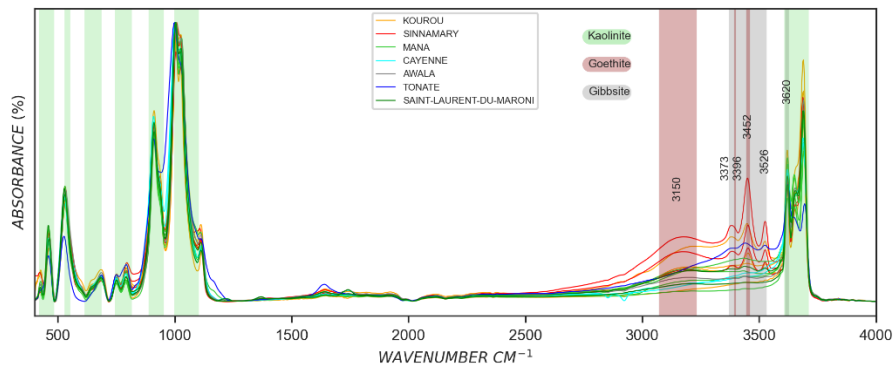


Fig. 3. : Infrared spectrum of the 17 lateritic soil

3.2 Identification of local biopolymer

The use of biopolymers to stabilize earthen constructions requires the consideration of various factors such as soil composition, shaping techniques, local biopolymer availability and extraction costs. The first step in this process was to identify all locally extractable biopolymers from waste or by-products known to stabilize earthen constructions. Five types of biopolymers were identified and are briefly presented below.

Biopolymer derived from animal :

Cow dung has been employed as a stabilizer in traditional earthen structures across multiple Asian and African countries with lateritic soils [19,34–36]. In French Guiana, the cattle sector totals around 18,000 animals, including Brahma zebus, cross-type cows (40%) and buffaloes (8%) [37]. To our knowledge, in French Guiana, cow dung is not currently harvested and may represent a suitable resource for earth stabilization.

Chitosan is a natural biopolymer present in shells of crustacea. It can be extracted through an alkaline deacetylation process, typically utilizing shells from discarded crustaceans such as crabs, shrimp or fish waste. Chitosan showed promising results to stabilize earthen materials [39]. The fishing sector represented the 3rd economic sector in French Guiana. Currently, waste and co-products of the fishing industry are not valued [40].

Biopolymer derived from plant :

Starch is found in several types of flours (rice, wheat, corn) and tubers (potatoes, cassava). Starch can stabilize earthen construction by binding soil aggregates together after heat-induced gelatinization [8,41,42]. This process has been used to stabilize lateritic clay with promising results [42]. With a production of 32,000 tons per year, cassava represents the leading crop produced in French Guiana. Cassava is used to prepare couac, a semolina made from peeled cassava roots. To our knowledge, cassava peels are not valued and could represent a suitable resource for starch extraction [43,44].

Mucilage from cacti and leaves has traditionally been used to improve the water resistance of earthen materials [21,45–47], but whether cactus mucilage could be used to stabilize lateritic soils is unknown. *Hylocereus undatus* is a species of hémipiphyte cactus from Central and South America, which is cultivated for its fruit, dragon fruit, also called pitaya. Pitaya cultivation is booming in French Guiana [48]. The mucilage-rich cladodes of these cacti are pruned annually and, according to local farmers interviewed for this study, the cut cladodes could represent an important resource to be valued.

Tannins are found in various plants and tree barks. Tannins have been used ancestrally to stabilize lateritic earthen construction due to a reaction between tannin and iron oxide [20–23]. Tannins can be extracted by boiling wood by-products. The timber industry represents the 2nd economic sector of French Guiana. Currently, co-products from sawmills, estimated at around 50,000 tons annually, are mainly used for energy production power plants but a fraction could potentially be repurposed to extract tannins [49].

3.3 Interaction tannin with two different soils

Before testing local biopolymers, we conducted preliminary tests using a well-known biopolymer, tannin, and two types of soil to evaluate how soil properties impact biopolymer stabilization. Tannin is known to form complex reactions with iron oxide [20–23]. Two soils with different iron content were mixed with tannins to observe a possible chemical reaction using infrared spectroscopy between the soil and the biopolymer. The first soil, M3, was collected from the quarry of Mana and had a low iron content of

6.4%. The second soil, S3, was extracted from the Sinamary quarry and had a high proportion of iron of 19.2%. In **Fig. 4**, the infrared spectrum of soil M3, soil S3, chestnut tannin, soil M3 and S3 mixed with 3% of tannin are presented. Soil S3 showed the characteristic peak of kaolinite, gibbsite, and goethite, while only kaolinite was identified in the M3 soil. Hydrolyzable tannin peaks were observed in the range of 1200-1800 cm^{-1} with the characteristic peaks of the aromatic ring C=C-C stretch at 1450, 1515, and 1605 cm^{-1} , the C=O ester bond at 1725 cm^{-1} and the C-O stretch at 1310 cm^{-1} [50]. The iron-poor M3 soil mixed with 3% tannin showed the same characteristic peaks of tannin in the range of 1200-1800 cm^{-1} with only a slight shift of the C-O stretch from 1310 to 1320 cm^{-1} . In contrast, the iron-rich soil S3 showed characteristic peaks of tannin, but with a considerable shift of the C-O stretches from 1310 to 1370 cm^{-1} . This shift suggest that complex reactions occurred between tannin and iron in the soil, as observed in previous studies [23,51]. In conclusion, these results suggest that the proportion of iron oxide in soils may significantly impact the chemical reaction between biopolymer and soil.

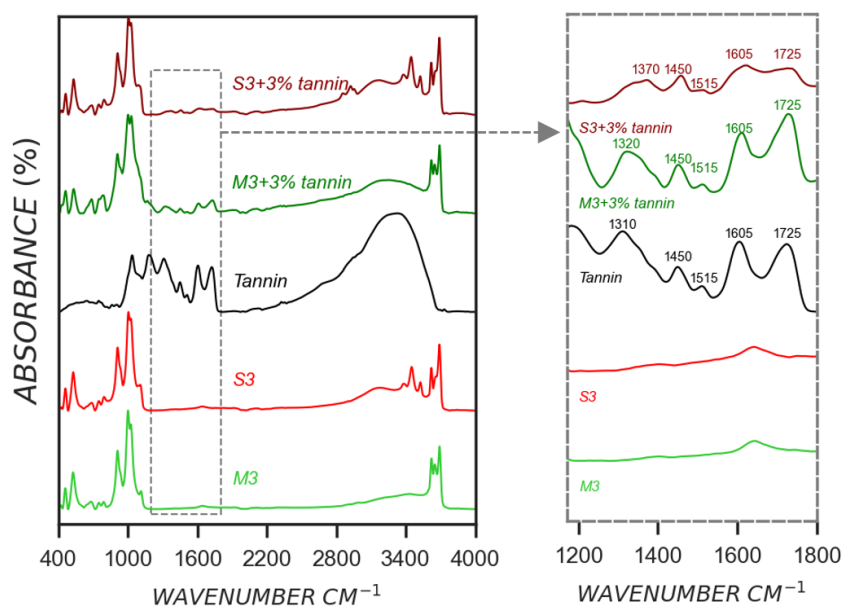


Fig. 4. Infrared spectra in the range of 400-4000 cm^{-1} of soil M3, soil S3, chestnut tannin, soil M3 mixed with 3% tannin, soil S3 mixed with 3% tannin, with a zoomed-in view of the range 1200-1800 cm^{-1}

4 Conclusion

This study highlights the potential of biopolymer stabilization for earthen construction in French Guiana. Results showed that all the soils were predominantly composed of SiO_2 , Al_2O_3 and Fe_2O_3 in different proportions and, among 17 soils, 6 were classified as laterite, 3 as kaolinite bauxitic and 3 as kaolinite. Local sources for biopolymer extraction were identified, including cow dung, chitosan from fish waste and crustacean shells, starch from cassava peel, mucilage from cactus and tannins from wood by-products. In addition, the study also showed that the proportion of iron in the soil could affect the reaction between biopolymers and soils. In conclusion, this study provides valuable insights into the potential of biopolymer stabilization for earthen construction in French Guiana and underscores the need for further research to determine the effectiveness of the five identified biopolymers in enhancing the water resistance of earthen construction in the region..

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