Natural additives and biopolymers for raw earth construction stabilization - a review

E. Losini[1]*, A. C. Grillet[1], M. Bellotto[2], M. Woloszyn[1], G. Dotelli[2]

1 Univ. Savoie Mont Blanc, CNRS, LOCIE, 73000 Chambéry, France

2 Politecnico di Milano, Dipartimento di Chimica, Materiali e Ingegneria Chimica "G.Natta" p.zza L. da Vinci 32, 20133 Milano, Italy.

*Corresponding author; e-mail: alessia.losini@univ-smb.fr

Contents

Abstract 2
1 Effects of the stabilization with biopolymers on the raw earth properties 6
  1.1 Biopolymers 8
    1.1.1 Polysaccharides 9
    1.1.2 Lipids 13
    1.1.3 Proteins 13
    1.1.4 Complex molecules 14
    1.1.5 The mixture of different biopolymers 16
  1.2 Fibers reinforcement 16
  1.3 Physical and Mechanical properties of samples stabilized with biopolymers 18
  1.4 Durability and hygrothermal properties of samples stabilized with biopolymers 20
2 The use of natural additives in mixtures preparations for different construction techniques 22
  2.1 Optimization of mixtures with natural additives for different applications 23
  2.2 Soil variability and natural additives suitability 24
  2.3 Issues of comparability between different research of additives' effects 25
  2.4 Biological vulnerability and sanitizing agents 26
3 Conclusions and new possibilities of research 26
4 Bibliography 29

Abstract

The importance of earthen construction materials lies in their widespread availability combined with a low embodied energy. Chemical stabilizers are commonly used to improve their durability and mechanical performance. The main drawbacks are the high environmental impact of their production, the loss of recyclability, and the possible reduction of raw earth's hygrothermal properties. Historically stabilization was achieved by the use of different kinds of fibers, agricultural wastes, and biopolymers incorporated into the earthen matrix.

The purpose of the present study is to review the state of the art of investigations on the influence of natural additives for raw earthen materials, to promote and facilitate future research in this field. More than 50 independent studies have been considered, including different types of raw earth constructions: plasters, adobe, compressed earth blocks and rammed earth. To enlarge the opportunity of investigating the use of biopolymers as stabilizers, some studies about soil stabilization have been included in the review. Results show that the use of recycled and waste material as a natural additive is promising direction for future research as it can provide a sustainable alternative to chemical stabilization.

Keywords:

Earthen construction, raw earth stabilization, natural fibers, biopolymers, waste materials, by-products, recycled materials.

Highlights:

Natural stabilizer's efficiency is related to the earth's composition.

The use of experimental framework and guidelines is advised for results comparison.

Biopolymers binds modify ductility, plasticity, viscosity, hydrophobicity and cohesion.

Need of a systematic frame to conduct studies and report material data is emphasized.

Microscopic interactions between clay and biopolymers require further investigations.

Abbreviation:

PL (Plasters), AD (adobe), CEB (compressed earth blocks), (RE) rammed earth, ST (soil stabilization), M (Mechanical properties), H (Hygroscopic properties) T (Thermal properties), D (Durability) and B (Biological risk).

Introduction and background

The reduction of the environmental impact of anthropic activities is one of the most important challenges of our century and the construction industry plays a significant role in this context. In 2017, the building and construction sector accounted for 36% of global final energy use, and about 40% of energy-related carbon dioxide (CO_2) emissions [1]. Moreover, the construction and demolition activities are the most impacting in waste generation in Europe, accounting for 35% of the total waste production [2]. The challenge of reducing the impact of buildings during their lifetime demands new efficient, sustainable, and reusable materials. In this context, raw earth as a building material has several advantages: local availability, low process-energy during the construction phase, and recyclability [3]. In addition to their low environmental impact, raw earth materials share some properties of interest for the operational phase of building life, such as high thermal mass and a capacity to buffer moisture variations. Indeed, a peculiarity of a raw earthen material is its high hygroscopic capacity, which allows water vapor to be absorbed and desorbed into the matrix. This property allows a passive regulation of the indoor environment, due to the water vapor exchanged between the walls and the air, until reaching a state of equilibrium with the environmental humidity and temperature [4].

The first downside of raw earth is the high material variability, due to local variability. Thus, for practical application, the soil is analyzed through qualitative field or laboratory tests, defining if its characteristics fit the requirements for a specific construction technique. Mechanical performance and durability are other issues of raw earth, highly sensitive to water. Construction technologies greatly contribute to ensure good resistance and protection against water uptake: from the moist ground with a stone basement, from the rain with a water-resistant roof, and from wind and rain erosion with a layer of render. A protective layer of lime render was historically used to preserve the walls against weathering. Chemical stabilization is another option that generally allows both water and mechanical resistance improvement, although some examples in the literature show that the mechanical resistance of plasters can be reduced by lime addition [5]–[9]. Lime has been used for centuries as stabilizer for earthen construction, as evidenced by the architectural heritage in Europe [10]. Cement is a more recent and widespread stabilizer, often used in combination with fibers, gypsum or fly ashes [6], [7], [11]–[16]. In the literature, many research works and reviews have been carried out on these chemical stabilizers [17]–[20]. However, the use of cement increases the embodied energy of the stabilized construction element, due to the energy-demanding process of cement production. It also causes problems of recyclability, because of the chemical reactions which turn earthen construction elements into artificial stones [21], [22]. Moreover, some studies attest that the hygrothermal properties can be modified by lime and cement-based stabilization, reducing the vapor permeability and the moisture buffer capacity of the material [23], [24].

Traditionally, fibers are mixed into earthen plasters using soil with high clay content, to reduce swelling and cracking. Meanwhile, the density of the material is reduced, improving the thermal resistance. The addition of sand is also commonly used to reduce shrinkage and to create a well-graded grain size distribution, both for plaster mixtures and load-bearing materials. Well-graded materials reach a higher level of density since grains of different dimensions can fill voids efficiently [25]. Consequently, the material presents both higher mechanical resistance and improved durability, thanks to the reduced porosity. Oil and fats are traditionally used as an external surface layer for render or flooring impermeabilization [4]. On account of their hydrophobic properties, oils, wax and fats coats can consistently improve the resistance against water and act as a waterproof agent [26]. Finally, some categories of biopolymers act as glue, increasing the cohesion so that they improve both earth strength and durability [27]. It should be mentioned that many studies deal with plasters that are stabilized to be used as an outdoor layer of render, or as efficient coating for bathroom surfaces or humid environments. The distinction between the indoor and outdoor applications, respectively as plaster or render, is not always specified in existing studies. Consequently, in the following, the original term used in the reviewed article will be reported.

In addition to traditional additives mentioned above, the availability of new natural additives, recycled and waste materials opens new fields of investigation on their suitability as stabilizers for earthen constructions, mainly as additives for mixture preparation and eventually as surface treatment products [28], [29].

Biopolymers are principally used in plasters and renders mixtures (animals' excrement, natural extracts from plants, proteins from animals' milk or blood), but little research on their properties and suitability for other techniques has been conducted. Consequently, little knowledge about the interaction mechanism between soils and biopolymers is available for the construction field. On the other hand, a large number of studies on soil stabilization for large infrastructures have been carried out using biopolymers. The need to use inexpensive and non-toxic materials that can be spread in the environment while respecting safety and durability requirements has drawn attention to natural wastes and additives. The mechanical strength and durability of materials are the main topics of this research, dealing with the stability of natural soils. These criteria are common with earthen construction; moreover, the technique for testing samples in the laboratory is similar to the RE and CEB procedures. However, this research does not provide information on hygrothermal properties and their possible modification as a consequence of biopolymer stabilization. Nevertheless, given the interest of improving mechanical properties, some studies on soil stabilization using biopolymers have been included, as an inspiration for earth construction.

This work aims to review the state of the art on natural additives for earth stabilization, promoting the use of waste and recycled materials historically used to reinforce earthen buildings. To overcome the issues of chemical stabilizers, alternative methods of stabilization of earthen materials are investigated, with particular attention to biopolymers that can ensure low environmental impact and future recyclability. The collection of new studies on natural additives and biopolymers can support the use of sustainable and traditional techniques of construction, presenting an attractive alternative for future research.

The research principally focused on the alternatives to chemical stabilization and the keywords for the research were 'biopolymers', 'natural fibers' 'natural additives' 'by-products 'waste material' 'recycled material' connected with the field of earthen construction and soil stabilization. Well known databases, such as 'Sciences direct', 'google scholar' were checked for peer-reviewed papers. The collected articles represent mainly years 1998-2019. After initial scanning of a large number of articles, finally only the most common construction techniques were retained: AD, RE, CEB, PL but also soil stabilization. In addition, several studies using additives that prevent recyclability were disregarded. Priority was given to studies with detailed raw material description and accurate characterization of the final element of construction. Available information on earth components and on the additives was extracted from the published papers and used in the present analyses. However, as there are no standard guidelines to report earth, additives and mixture characteristics it was not always possible to report all data of interest. Consequently, the present work will also evidence the need for a more systematic approach in the studies to allow easier data comparison and results extrapolation.

The present review collects more than 50 articles and additional literature is mentioned to complete and explain some specific topics. A similar percentage of articles deals with AD and CEB, respectively the 30% and 26%. The same percentage of 18% represents PL and ST, a smaller percentage of 8% deals with RE. The first part of the review deals with natural additives for stabilization and their principal effects on raw earth properties (chapter 1). The second section focuses on the discussion about their use in different construction techniques, the optimization of the mixtures by using biopolymers, the issues of results comparison between different studies, and the biological vulnerability (chapter 2).

1 Effects of the stabilization with biopolymers on the raw earth properties

The natural additives presented in this review include principally biopolymers, mainly by-products and waste from agriculture and industrial production, that can be promising additives for earth stabilization. The use of fibers, included in the biopolymers group, mainly as a polysaccharide (cellulose) or keratin (protein), is discussed separately, to evidence their specific function.

More than 30 studies out of 50 involve by-products or waste materials with different origins. Table 1 reports all the additives presented in the analyzed studies, considering their origin as waste (W) or by-product (BY). Wastes are defined as materials without market value that can require high management costs to be discharged, while by-products are secondary outputs of a manufacturing process that have a lower market value than the principal output. As an example, Posidonia sea-plants deposits on sea-coast are considered as a waste to be transported and discharged with some cost [30]. However, the market value is not always reported in the studies, the classification between waste and by-product is sometimes unclear, or both terms are used as synonymous. For all these uncertain cases, the double classification W/BY is reported in Table 1.

When no origin is specified in the study, the natural additive probably has a market value or is taken from the natural environment, as in the case of wild plant fibers [31], [32]. Such cases are noted in Table 1 as (-). A dedicated column reports the main properties analyzed to investigate the effect of the additive, divided into mechanical (M), hygroscopic (H), thermal properties (T), and investigations on the durability (D) and biological vulnerability (B). Forty-five very diverse additives are shown in Table 1. For most of them mechanical properties are reported, while additional characterizations are performed only for some of the additives.

Table 1 Natural additives and fibers for earthen material stabilization classified by their additive source: waste materials (W), by-product (BY), case of uncertain classification (W/BY) or not specified in the article (-). M (Mechanical properties), H (Hygroscopic) T (Thermal properties), D (Durability) and B (Biological risk).

Additive type	**Additive source (W/BY)**	**Main effects studied**	**Reference**
Plant origin			
pine needles	-	M	[31]
kenaf fibers, hibiscus cannabinus fibers	-	M D T	[33], [34]
thypha spadixes wool fibers	-	M H T	[32], [35]
hemp fibers	-	M	[13]
falx fibers	-	M	[13]
chips of phragmites and thypha spadixes	-	H	[32]
bamboo particles	-	M D	[36], [37]
oat fibers	W/BY	M H T B D	[8], [35]
sunflower bark, pith	W/BY	M H T D	[38]
banana fibers	W	M	[15]
pineapple leaves	W	M D	[14]
coconut husk	W	M D	[39]
sugarcane bagasse	W	M D	[39]
cassava peels	W	M D	[40]
fescue	BY	M	[41]
rice husk	W	M D	[42]
wheat straw	W/BY	M T D	[11], [43]–[45]
rape straw	W/BY	M H T D	[38]
barley straw	W/BY	M H T D B	[43], [44], [46]–[48]
straw fibers	W/BY	M D	[41], [42], [49]
lavender straw	W/BY	M T D B	[48]
corn plant	W/BY	M	[41]
corn pith	W/BY	H T	[46]
oil palm fruit, bunch	W/BY	M D	[14], [39]
date palm fibers	W/BY	M D	[16], [42]
olive fibers	W	H T	[50]
olive stones	BY	M	[41]
burned olive waste	W	M D	[51]
wood shavings	W	M D	[42], [43]
seaweeds fibers	W	M D	[52]
posidonia seagrass	W	M	[49]
carrageenan	-	M D	[53]
guar	-	M	[54]
xanthan gum	-	M	[54]–[56]
gellan and agar gum	-	M D	[57]
alginate	-	M	[58], [59]

tannins	-	M	[60], [61]
residues of beetroot and tomatoes	W	M D	[52]
lignin/lignin sulfonate	BY	M D	[58], [62], [63][64] [65]
cooking oil	W	M	[7]
linseed oil	-	H D	[4]
Animal origin			
pig hair	W	M	[66]
wool sheep fibers	W/BY	M	[45], [58], [67]
chitosan	BY	M D	[28]
casein and sodium caseinate biopolymers	-	M	[68]
cow-dung	W	M D	[69]
cow blood	BY	M	[70]

Stabilization can be considered as a modification of the physical and/or chemical earth parameters that can improve one or more characteristics of the material [4], [39]. Modifications of density and porosity during stabilization with biopolymers can have a high impact on material performances. As an example, the density can be strongly modified by the stabilization process influencing both, the mechanical resistance and thermal behavior. Similarly, the porosity affects the structure of the materials and indirectly the durability, the mechanical and hygrothermal properties. Moreover, the porosity influences directly the capillarity of the system and its resistance against water. As an example, the mechanical resistance is related to the suction properties of the material, that are characterized by its pore size distribution [71], [72]. The use of biopolymers can modify the global porosity or only the porosity distribution, changing material performances [52]. Biopolymers can modify the pore size distribution with different mechanisms: filling the smallest pore, improving the packing of soil particles by gluing them together, or modifying the rheology of the system [34], [52], [55], [69]. It is also important to consider that, when using additives, a lower bulk density does not always correspond to a higher porosity, because the voids can be filled by lighter materials of the additives in the mixture [52].

1.1 Biopolymers

Biopolymers are produced from living beings and they can have very different features: plant or animal origin, hydrophilic, hydrophobic, or amphiphilic behavior. As Vissac et al. [27] suggest a possible classification of biopolymers includes polysaccharides, proteins, lipids, and other complex molecules. Table 2 reports different typologies of biopolymers, with the respective percentage of addition for each study analyzed. Among the analyzed studies, the added amount is between 1-3 wt% for the liquid additives and can reach a higher percentage when the liquid substitutes the addition of water (cow blood at 6.08 wt% and alginate at 19.75 wt%) [58], [70]. Other cases of a high percentage of addition are the use of lignin up to 15 wt% and residues of beetroot and tomatoes at 10 wt%, probably due to the low clay content in the soil that required to be replaced by an additional binder [52], [64], [65]. Results in Table 2 also show a relationship between the type of additives and the construction technique. Indeed, the solid additives (e.g. cow-dung and vegetable residues) are used for AD preparation only, while the liquid or powders formulations are mainly used by CEB, RE and ST studies (Table 2).

Table 2 Biopolymers, classified into different categories, with a dedicated column for the technique: AD (adobe), CEB (compressed earth blocks), (RE) rammed earth and ST (soil stabilization). The additive addition is reported as wt% with respect to the total mixture.

Additive type	Additive (wt%)	Technique	Reference
polysaccharides and gelling biopolymers			
chitosan	0.5-3	AD	[28]
guar and xanthan gums	0.25-3	RE	[54]
gellan and agar gum	1-3	ST	[57]
xanthan gum	0.5-1-1.5-2-2.5	ST	[55]
xanthan gum	0.5-1-1.5	ST	[56]
carrageenan	0.05-0.1-0.2	AD	[53]
alginate	19.75	CEB	[58]
alginate	3	3Dprinter	[59]
proteins			
casein and sodium caseinate	0.5-1-2-3- 5	ST	[68]
cow blood	6.08	RE	[70]
lipids			
cooking oil	1	RE	[7]
linseed oil	5	RE	[4]
complex molecules			
lignum	0.5	CEB	[58]
tannins	1.14	CEB	[60] [61]
lignin sulfonate	0-0.5-1-2-3- 4	ST	[62]
lignin sulfonate	0.5-4	ST	[63]
lignin based product	2-5-8-12- 15	ST	[65] [64]
residues of beetroot and tomatoes	10	AD	[52]
cow-dung	0-3	AD	[69]

1.1.1 Polysaccharides

Polysaccharides are represented by the macromolecules from the family of the complex sugars and the long chains of simple sugars that can have a structural role (cellulose and chitin) or an energy storage function (starch). To interact with clay, they should be prepared to help the long chains to be released from their organized structure, traditionally through a maceration procedure. When added to the mixture, they are thus able to collect different mineral particles creating a web that acts as microscopical reinforcement [27]. Natural fibers, excrement, gums, vegetable glues, juice, and seagrass fibers belong to the family of polysaccharides. Natural fibers can also act as a macroscopic mechanical reinforcement due to their shape and strength and will be discussed later, in Table 3 and paragraph 1.2.

Some traditional techniques use polysaccharides mainly to enhance plasters resistance against weathering, such as the mixing of fermented rice husk in the tradition of Mali or the mixing of fine paper pulp in the Japanese one [27]. Similarly, vegetables that produce gels when mixed with water are used in Ghana and Burkina Faso to obtain glue water to add to the mixture. Once dried, the admixture acts as a glue connecting the soil particles [27]. Starch is another typology of polysaccharide contained in different flours (rice, wheat, corn) and tubers (potatoes, manioc). It can form a glue when heated and acts as a rheo-fluidifiant: it is more fluid when mixed. Starch can be used in the same way as glue water and gels to help weathering durability [27]. In addition to fibers, Table 2 reports some biopolymers tested for raw earthen stabilization.

Chitosan

Chitosan is produced from the chitin by alkaline deacetylation treatment, often using discarded crab, shrimp, and crustacean shells obtained from the food industry wastes [22]. It is used as a filming agent in the food industry and the pharmaceutical sector. Chitosan is hydrophobic and is insoluble in water, and it can be used as a cover layer to prevent water erosion. Aguilar et al. [28] studied the effect of the chitosan as a coating layer or mixed into the matrix at 0.5 and 3 wt%, with promising results for the improvement of the mechanical and durability properties.

Gums

This typology of polysaccharides is mainly used as food additives and rheology modifiers. Once mixed with water under determinate conditions to dissolve and gelling, it is possible to use this liquid directly for mixing soil. These polysaccharides can interact with clays by hydrogen bonding or electrostatic interactions, respectively, for neutral or negative gum typology. These molecules are long and branched, so they can link with several mineral particles. Moreover, during the drying phase, evaporation increases the concentration of the biopolymer hydrogel. The final material resistance is given by the strength of the hydrogel and its interactions with soil grains [57].

Thermo-gelating biopolymers: agar and gellan gums

Chang et al. [57] studied thermo-gelation of biopolymers, in particular, agar gum and gellan gum. Agar gum, also called agar-agar, is a hydrophilic colloid extracted from red seaweed that dissolves in boiling water and forms a gel when cooled to a lower temperature [57]. Gellan gum is a water-soluble gum and it is produced by the aerobic fermentation of a particular microorganism. Gellan gum, under appropriate conditions, behaves as a thermo-reversible gel [73]. Thermo-gelating biopolymers showed good effects, enhancing earth strength and earth durability, in particular for soils with higher fine content, *"due to the microscopic interactions (e.g., hydrogen bonding) between fine particles and biopolymers"* [57].

Guar and xanthan gums

Xanthan gum is a water-soluble gum produced by the bacterium Xanthomonas campestris, used for food and pharmaceutical applications [74]. Guar gum is extracted from a plant called Guar, belonging to the Leguminosae family. Muguda et al. [54] tested the addition of two biopolymers: guar and xanthan gums. For samples treated with 2 wt% of these biopolymers, the unconfined compressive strength after seven days was found higher than for samples stabilized with 8 wt% of cement, respectively by 30 wt% and 50 wt% for guar and xanthan gum, while only xanthan gum increased tensile strength. The study assesses that the combination of two different phenomena could explain the improved performances: suction and hydrogel bonding that generates higher suction and strength in the stabilized samples against the control specimens [54]. Moreover a study on the assessment of the potential recyclability of earth stabilized with biopolymers [75], confirmed that washing the soil treated with guar gum was sufficient to recycle and get back to the original earth gradation and plasticity.

Chang et al. [56] found that xanthan gum is more effective with fine particles by enhancing strength due to hydrogen bonding, which allows fine clay particles and biopolymer matrix to behave as a cementitious binder connecting coarse particles. Latifi et al. [55] studied the underlying mechanisms of stabilization of xanthan gums with a series of macro and microstructural experiments. Their results show that the formation of a new cementitious product takes place through chemical reactions that occur between xanthan gum and the soil particles. Moreover, the study realized a series of experiments on soil stabilization using two different clays, bentonite and kaolin, finding two different optimum additions for both soils [55]. Similarly, Chang et al. [56] found that the soil composition is important for chemical bonding and mechanical friction, testing xanthan gum for soil stabilization.

Carrageenan and alginate

Carrageenan is a hydrocolloid extracted from seaweed, with wide use in the food industry for its gelling and stabilizing action, particularly in dairy and meat production [76]. Alginate can be similarly extracted from different species of brown algae and more recently produced by bacteria through biosynthesis; it is used in the food industry, pharmaceutical and printing sectors [77]. Some traditional recipes for earthen plasters are made with this kind of biopolymer [27]. Perrot et al. [59] positively tested the use of alginate at 3 wt% as a fast setting binder for 3D printing. This case study was included to show one non-traditional technique, where biopolymers can facilitate and make faster the hardening of the material, saving time during the construction phase. Indeed, 3D printing is a modern technology that exploits a plastic mixture to build directly load-bearing walls, layer upon layer [78]. The water content required for this technique is very high, 45%, close to the liquid limit of 48%, due to the necessity of continuously pouring the mixture through the printer [79]. The addition of alginate was successfully tested to provide fast structural build-up of earth, instead of using cement or hydraulic binders, while the compressive strength of the material remained almost the same [79]. A different behavior was found using a higher quantity of alginate for CEB preparation by Galán-Marín et al. [58]. They showed that the addition of alginate in a higher quantity (19.75 wt%) increases the compressive strength by 69% (from 2.23 to 3.77 MPa), while the flexural strength remains almost the same. Nakamatsu et al. [53] obtained a similar result using carrageenan, which seems to be effective also for increasing the tensile strength. The biopolymer dispersed in low quantities (0.5-1-2 wt%) in water enhanced the compressive strength up to 85% and the tensile strength up to 52%. At the same time, an increase in the water repellence and erosion resistance was observed, for both ways of using carrageenan: coating the samples or incorporating it within the matrix. However, the reasons of this behavior were not explained. Additional studies are needed to investigate the possible mechanisms responsible for the improvement of the mechanical strength.

1.1.2 Lipids

The main characteristic of lipids is that they are insoluble in water. They can be completely hydrophobic or amphiphilic. Oil, fats and butter can have an animal or vegetal origin. Thanks to their hydrophobicity, these additives were used as waterproof coating surfaces. The most used are linseed oil and shea butter, followed by kapok oil, grapeseed oil, fish oil bee, and carnauba wax [27]. Because of the expensiveness of these products, their use is quite limited and reserved for finishes and coating layers. Minke et al. [4] tested the use of double-boiled linseed oil for loan surfaces, obtaining a high degree of weather protection and strength against abrasion, although the vapor permeability is heavily reduced. Eires et al. [7] tested the cooking oil by soya beans decanted after its use. The results of its addition in combination with quicklime gave good results in terms of strength and water resistance, even if its use is not recommended for internal walls due to the fungi growth.

1.1.3 Proteins

Proteins are animal or plant molecules constituted by a sequence of amino acids. Casein from milk and cheese, albumin (from eggs, milk, or blood), collagen, and keratin are all proteins. The amphiphilic proteins interact with clays thanks to their amphiphilic nature. The hydrophilic part can be absorbed by the fine particles of clay covered by water molecules, while the hydrophobic one is directed toward the external layer that shows an increased water resistance [25], [27]. Animal fibers, made of keratin, will be discussed in section 1.3 dedicated to fibers' behavior.

Casein can be produced from spoiled cow milk and it constitutes a large part of the milk proteins. Fatehi et al. [68] tested the suitability of two protein-based biopolymers for soil stabilization: casein and sodium caseinate. Although casein is insoluble in water, when mixed with sodium hydroxide, the reaction produces sodium caseinate salt, which is a water-soluble glue. The study showed good results in stabilizing dune, and the effect was compared with the one obtained after the addition of gellan, agar, xanthan, and lignin. The higher performances for mechanical resistance were obtained using 1 wt% of agar gum and xanthan gel, followed by casein, sodium caseinate, and gellan gum. All these values were significantly higher than the mechanical performances of the earth stabilized with 5 wt% of lignin [68]. According to the study, casein and sodium caseinate can paste soil grains to each other thanks to a different mechanism of adhesion: Van der Waals and electrostatic interactions, complex bond between activated protein groups, and sand particles. ‘*The sodium caseinate particles with a complex structure coat the grain surfaces and charged sodium caseinate to attach to soil particles so that the high strength mixture would be formed by having strong bonds’* [68]. Casein is used to improve plasters' water-resistance, often combined with lime: this mix forms a waterproof chemical agent called lime albuminate [4]. It should be reminded that the use of this additive reduces the vapor diffusion permeability of the plasters, as happens using linseed oil.

Kraus et al. [70] tested the use of blood as a stabilizer for rammed earth, preparing a set of samples with the optimum water content and a second one using blood instead of water. After a drying period of 28 days, the mechanical resistance of the stabilized samples exceeded the control ones by approximately 36%. According to the author, when blood dries out, coagulation appears to be hardening the matrix and increasing the global strength of the sample. The microscopic interactions responsible for the mechanism adding strength require further studies and observation.

1.1.4 Complex molecules

Tannins

Tannins are complex molecules, present in almost all plants and extracted to be used in different industrial sectors: leather, wine, animal feed additive, and beer production. Tannins are soluble, mainly composed of phenols, with an aromatic and hydroxyl group. The hydroxyl group can bring a negative charge, according to the pH of the environment. In this case, this part of the tannins molecule acts as a clamp and closes a cation, leading to chelation, a lower ionic force, and clay dispersion. Moreover, tannins can react with Fe3+ ions forming iron tannate, increasing the solubility of multivalent iron ions. These multivalent ions can increase the charge density of clays’ structural layers, reducing swelling, and increase the material water resistance [27]. Some traditional recipes use boiling seeds from local plants (form néré or carobs) to release tannins in the water to be used as stabilizers. The addition of limonite stones rich in iron oxide is typical of Burkina Faso traditional practices, to allow the formation of iron tannate. The same reaction has been studied using soil naturally enriched in iron minerals. Banakinao et al. [80] tested the use of husk of néré plant to stabilize four different soils for constructions in West Africa. The husk of the néré (Parkia-biglobosa) is an agricultural waste of juice production that has a high content of tannins. This low-cost material is used to produce husk powder of néré suitable for soil stabilization. The results are interesting for the improvement of compressive strength and water resistance characteristics. Keita et al. [60] studied the same material on a different soil of Burkina Faso with high contents of iron hydroxide minerals. The study assessed that the formation of tannin macromolecular complexes with iron from goethite and hematite increased the failure stress by about 22%. The same behavior was found by Sorgho with a different kind of African clay, always rich in iron minerals as goethite and ferrihydrite [61].

Lignin and lignin sulfonate

Cellulose, hemicellulose, and lignin are the main components of plants and fibers. Lignin can be classified as a phenolic biopolymer, belonging to the family of aromatics compounds. Some industrial processes have made accessible large quantities of by-products that can be used for soil stabilization. Lignin is a by-product of paper production, that separates the cellulose from the lignin with different chemical processes [81]. Lignin sulfonate is involved in 3 studies out of 50 considered [58], [62], [63]. Ta'negonbadi [63] reported that lignin sulfonate used to stabilize clay soil could increase the mechanical strength up to 44% at the optimum of 0.75%. An interesting study about soil stabilization with lignin instead of quicklime found that this biopolymer enhances ground resistance. The costs of soil stabilization using lignin at 12 wt% instead of quicklime at 8 wt% are decreased by ten times, still ensuring a high load-bearing capacity [64]. Cai et al. [65] studied the stabilization of silt using lignin, with good results for the mechanical strength after seven days of drying. According to the study, a possible mechanism of stabilization was proposed, although it will require further analysis to be confirmed and it corresponds with the microchemical analysis carried out by Indraratna et al. [82]: the improvement of performance exhibited by the treated soil could be attributed to the reduction of the clay's double layer thickness by the neutralization of surface charges of the soil particles and the subsequent formation of stable particle clusters.

1.1.5 The mixture of different biopolymers

The animals that use earth and fibers for their nest combine them with their excrements that contain food residues, mainly of vegetable origins. They obtain a structure that can resist weathering and shows a good strength. Taking inspiration from the animals, it is possible to mix different components to test the combined effects of more than one biopolymer, trying to emulate the performative strategy of animals. An interesting case is the use of seaweed fibers combined with beetroot and tomato residues at 10 wt% [52]. In this case, natural polymers can reduce the porosity filling the smallest pores and increase the mechanical strength and durability.

Cow-dung is a traditional additive composed of partially decomposed cellulose fibers, organic amine compounds, microbes, and microorganisms that come from the animal intestine. [27], [69]. It is used mainly as a fertilizer for agricultural purposes or as fuel during combustion. Moreover, after a maceration period, it can be used as a natural additive rich in cellulose fibers of different sizes and dimensions. This practice is mainly used to improve weathering resistance for raw earth plasters [4]. It is spread in Africa, Europe, Asia, Latin, and North America [12]. Although the wide diffusion, little research has been done on this traditional technique. Millogo et al. [69] showed that cow-dung reacts with kaolin and fine quarts to produce insoluble silicate amines. This reaction is responsible for the aggregation of single soil particles and it produces an apparent reduction of porosity and a significant improvement of water resistance and mechanical strength.

1.2 Fibers reinforcement

Table 3 reports the fibers' content for each study analyzed, showing the quantity of fibers used as wt% and their length when the information is available. Low fiber content ranges within 0-3 wt% and is more common for CEB production, where a compaction method is applied. Intermediate values of fiber content around 3-6 wt% are mostly used with AD technique (Table 3), a molding procedure to prepare bricks. In the manufacturing process for AD technique, higher water content is used as compared to the compaction technique, helping the adhesion of the fibers with the clay particles. The high percentages of fibers added to the mixture ranging between 6-30 wt% are found principally for PL mixtures preparation, as reported in Table 3. Many studies investigate a wide range of fibers addition, that can vary due to the soil composition and the fiber typology.

It should be mentioned that the addition of fibers in high quantity presents a technical difficulty in the manufacturing process. Indeed, fibers aggregate themselves, as frequently happens with wool fibers, and uniform mixing of a high quantity of fibers with the soil is difficult. For this reason, low percentages of fibers are more common especially for longer fibers. As an example, the banana fibers added at 0.35 wt% have a range of length between 50 and 100 mm [15]. Differently, when the fibers are shorter and the mixture is used for PL the fibers content can rise up to 12-30 wt%, as in the case of wood shaving particles and sunflower pith [38] [50] [43]. Such high quantity of fibers (6-30%) is used to reduce the cracking of plasters during shrinkage and to improve their hygrothermal properties. The influence of fibers on material properties is discussed in the next section, enriched with a comparison with the effects of other biopolymers. Further considerations about the use of additives for the different construction techniques are developed in section 2.1.

Table 3 Fibers for earth constructions as wt% with respect to the total mixture, with a dedicated column for the used technique of construction: adobe (AD), plasters (PL), and compressed earth blocks (CEB). The length of fibers has been reported in a dedicated column, (-) indicated the data missing in the reference.

Additive type	**Fibers (%)**	**Fibers length (mm)**	**Technique**	**Reference**
Low content - below 3 (wt% dry matter)				
banana fibers	0.35	50-60-70-80-90-100	CEB	[15]
date palm fibers	0.20	20-35	CEB	[16]
hibiscus cannabinus fibers	0.2-0.8	30-60	CEB	[34]
barley straw	0.56	-	PL	[47]
barley straw and corn pith	2	1-2	PL/CEB	[46]
posidonia seagrass, straw	3	30-190	AD	[49]
oat fibers and typha spadixes, typha fiber-wool	0.1-1	20	PL	[35]
wool sheep fibers	0.25-0.5	10	CEB	[58]
pineapple leaves and oil palm fruit bunch	0.25-0.75	10	CEB	[14]
sugarcane bagasse (SB), oil palm fruit (OP), and coconut husk (CH)	0.25-1	80 (SB), 30 (OP),50 (CH)	CEB	[39]
kenaf fibers	0.2-0.8	30	CEB	[33]
rice husk	0.3-0.9	-	AD	[42]
straw, palm fiber, wood chips	0.3-0.9	10-40	AD	[42]
pig hair	0.5-2	7-15-30	AD	[66]
chips of typha and phragmites	0.25-2	2-20	PL	[32]
corn plant, fescue, straw fibers	1-3	-	AD	[41]
wheat straw	1-2	-	CEB	[11]
wheat and barley straw	1-3	40	CEB	[44]
oat fibers	1	10-20	PL	[8]
Intermediate content - between 3 and 6 (wt% dry matter)				
hemp fibers, falx fibers, gypsum	3	-	AD	[13]
wool sheep Sardinia	2-3	10-20-30	AD	[67]
cassava peels	2.5-5	50	CEB	[40]

bamboo particles	2-6	-	AD	[36], [37]
barley straw, lavender straw	3-6	10	AD	[48]
wheat straw, wool sheep	3	-	AD	[45]
High content - above 6 (wt% dry matter)				
olive fibers	4-12	20	PL	[50]
seaweeds fibers and residues of beetroot and tomatoes	10	10	AD	[52]
barley straw, wheat straw	2-16	50	PL	[43]
wood shavings	2-17	20	PL	[43]
rape straw, sunflower bark, sunflower pith	30	15	PL	[38]
pine needles	25 (volume%)	1.42-4.46	AD	[31]

1.3 Physical and Mechanical properties of samples stabilized with biopolymers

In general, for non-stabilized raw earth materials, the mechanical strength is mainly increased with higher density and lower porosity. When the stabilization process modifies these two parameters, the compressive strength usually raises. This effect can be generated by higher compaction effort, a well-graded grain size distribution and biopolymers able to fill the porosity in the material. Moreover, a modification in the global porosity or porosity distribution can influence the suction, thus the mechanical strength [54]. Thanks to other mechanisms, biopolymers can glue the particles together and increase the mechanical strength without increasing the density of the material. As an example, two studies report a lower bulk density achieved thanks to the additives (lignin sulfonate and vegetable waste with seaweed fibers), combined with a higher mechanical result [52], [63]. Other studies give a first assessment of the creation of hydrogen bonding or chemical reactions between the clay particles and a biopolymer, that could form stable particle clusters, explaining the increased mechanical strength [51], [55], [56], [60], [61], [65], [68], [69], [82], [83].

Fibers' addition is not always favorable to enhance mechanical resistance, and their suitability should be evaluated case by case. Their efficiency depends on fiber's typology, quantity, and length [15], [34], [58], [67], [84]. If the addition of fiber is optimized, good results can be obtained thanks to their ductility and their ability to connect the matrix and reduce cracking. Moreover, the fibers can generate a higher residual strength after failure [67], [85]. As an example, Olacia et al. [49] found an improvement of around 50% in mechanical strength when Posidonia Oceanica sea-plant fibers are used with a percentage of 1.50 wt% content (investigated percentage of addition 0-0.5-1.5 and 3 wt%). Similarly, the optimized use of palm fiber and straw raised the compressive strength respectively to 156%, and 35%, while the use of rice husk decreased the compressive strength by 41% against control specimens (investigated percentage of addition between 0.3-0.6 and 0.9 wt%) [42]. The different effect of rice husk was probably caused by its small size, more similar to particles than fibers, creating additional distance between the soil particles and decreasing the adhesion of the matrix, with higher formation of cracks. Contrary, the positive effect of palm fibers was probably caused by the ability of the longer fibers (10-40 mm) to interconnect the clay particles and prevent cracking when drying, as well as the tensile resistance of the fiber. The palm fiber length is about 10 times its diameter (1-2 mm), this ratio is even higher (approximately 20) for straw fibers. Moreover, the tensile stress of palm fibers was evaluated at 65.1 MPa against the lower values of 30-50 MPa of straw fibers. The reported results suggest that the characteristics of the fiber in terms of tensile stress and slenderness generate different effects in the mechanical properties, by possibly improved cohesion due to the fibers that connect the matrix and decrease the cracking.

A similar difference in the mechanical strength modification was found in the studies that involve animal fibers [45], [58], [66], [67]. Animal fibers are made of keratin, a protein insoluble in water. Sheep fibers from farm animals for milk production are not suitable for the textile industry and this material can be used for insulating panels in the building sector. Galan-Marin et al. [58] tested the incorporation of these fibers in CEB combined with alginate. They found that the mechanical strength was improved by 37% using a low percentage of wool (0.25 wt%) [58]. Aymerich et al. [67] extended the research on wool fibers demonstrating that their addition enhances the residual strength, ductility and absorbed energy. The residual strength is the load that the material can still carry after a first failure and damage without failing. Differently, ductility is the ability to undergo significant plastic deformation before reaching the failure point. In another study, pig fibers used for adobe preparation showed a reduction of the flexural and compressive strength, especially for higher percentages of fiber addition and length [66]. In this case, the reduction of the compressive strength was probably caused by the formation of porosity clusters due to fibers addition that are not uniformly distributed and can modify the pore size distribution of the soil. At the same time, the addition of the fiber reduced the brittle behavior of the soil and increased the flexural toughness, reducing shrinkage and cracking. A lower dosage and shorter fibers length was then recommended to improve the toughness of the material without high compromise the compressive strength [66].

To conclude, the use of fibers to improve the mechanical properties of the material is not always suitable and the mechanism related to the efficiency of the fiber should be investigated case by case. As assessed by Laborel-Peron et al. [85], their effect in the mixture depends on the type of natural fiber and its geometry that can facilitate the adhesion with the particles. If this adhesion is not effective, the clay particles are less interconnected due to the space created by the fibers. The porosity increases and friction between the grains is reduced, crating lower compressive strength. This effect could be accentuated by the swelling of the fibers due to water absorption during the mixture preparation and the consequent reduction of the volume when drying, which creates voids in the matrix [85]. Future research on fiber properties could help explaining differences in the effect of reinforcement depending on the nature of the fiber.

1.4 Durability and hygrothermal properties of samples stabilized with biopolymers

Among the analyzed studies, different typologies of biopolymer were tested to enhance the soil durability and ameliorate their hygrothermal properties, as reported in the extended list presented in Table 1. Biopolymers that show promising results to enhance water-resistance are linseed oil [4], cooking oil [7], seaweeds fibers and residues of beetroot and tomatoes [52], carrageenan [53], lignin sulfonate [63], casein and sodium caseinate biopolymers [68], cow-dung [69], chitosan as coating layer or mixed into the matrix at 3 wt% [28]. In some cases, the cohesion of the material is increased by the additives, which can fill small porosity and glue the grains together, thus resisting better against weathering and capillarity raises. For example, Achenza et al. [52] observed that the samples reinforced with seaweed fibers and residues of beetroot and tomatoes can endure 8 days until reaching a stable weight atsaturation water content, while fibers stabilized samples disintegrated just after dipping[52]. Other studies show that fibers, when the adhesion with clay is good, can also enhance water resistance, in particular, if the fibers are not subjected to high water absorption and swelling. At the same time, fibers addition has a positive effect on decreasing the density and the thermal conductivity and often the length of the fibers influence these two properties [8], [34], [35], [38], [44], [46], [50]. As an example, Millogo et al. [34] tested the use of hibiscus fibers against erosion, finding that the samples reinforced with 60 mm fibers were more eroded than those with shorter fibers. Brouard et al. [38] observed that water absorption has a strong relationship with porosity distribution and fiber absorption capacity. Moreover, as Jovè-Sandoval et al. [31] assess, the surface of the fiber is an important variable: a smooth surface does not improve the adhesion between clay and fibers. The same study shows also that the fiber shape can help the adhesion with the clayish mass, for instance in the case of the pine needle whose surface has a convex beam and a concave underside. A further point that arises from many studies is the importance of preliminary analysis on fibers: smoothness, porosity, shape, length, diameter, density, water absorption, thermal conductivity, and tensile strength resistance. These data can help to predict their behavior when mixed with clay. As an example, the use of lavender straw at 3 wt% showed better results of mechanical resistance and durability as compared to barley straw, which shows better performance for reducing the thermal conductivity. This behavior is probably due to the denser microstructure of the lavender straw, its rough surface that favors the adhesion with the earth, and probably its chemical composition [48].

Hygrothermal properties are more investigated when fibers biopolymers are used, probably because fibers contribute to decrease the bulk density and to increase the porosity interconnection, thus reducing the thermal conductivity [8], [86]. The use of fibers seems to have a positive effect on the hygrothermal properties of the material and the full list of the studies that considered this topic is reported in Table 1. Generally, increasing the amount of fibers reduces the thermal conductivity, and in some cases, increasing the length of fibers generates the same effect [34]. As an example, the addition of barley and wheat straw fibers with percentage from 0 to 3 wt% caused a decrease of the thermal conductivity by about 35-34% in comparison to earth bricks without fibers reinforcement [44]. Considering plasters incorporating corn pith, a significant reduction in thermal conductivity was observed (60% and 78% on average in samples incorporating 1 and 2 wt% of granulate respectively). Similar results with barley straw (36% and 60% of reduction when barley was added at 1 and 2 wt% respectively) were observed by [46]. The use of a light biocomposite (sunflower pith aggregates) gave the best result among all the materials considered for reducing thermal conductivity, probably due to the high quantity of addition (30 wt%), while showing a poor compressive strength [38]. The use of typha fibers had a positive impact on hygroscopic properties, increasing and accelerating moisture adsorption and desorption [32], [35]. The dynamic MBV (Moisture Buffer Value, [87]) test evidenced that the addition of thypa fibers contributed to decrease the desorption delay, reducing the risk of hysteresis phenomenon during multiple cycles [35]. Liuzzi et al. found that the use of olive leaf fibers increased the adsorbed moisture content, especially in the range above 80% RH, measuring both the dynamic ideal MBV and the sorption isotherm [50], [87].

2 The use of natural additives in mixtures preparations for different construction techniques

The present section illustrates the different use of natural stabilizers for raw earth stabilization in construction techniques: PL (plasters), AD (adobe), CEB (compressed earth blocks), RE (rammed earth). As mentioned, some studies about ST (soil stabilization) were included in the present review to show new interesting materials that could be used for earthen construction. This consideration is valid principally for RE and CEB, which share with ST a similar method for sample preparation, and thus, comparable performances. The distinction between AD and CEB, a modular element of raw earth, was based on the manufacturing by molding and compression, respectively. A further distinction for molding technique is the casting procedure that allows pouring almost liquid mixture into the formwork, more used in case of boards production [88].

Samples preparation is necessary to test the performances and properties of a specific construction element; therefore it is related to the material and the technique used for the construction. This procedure can be divided into two main steps: mixture preparation for mixing soil and additives, and a phase to give the final shape to the element. The typology of additive and mixture preparation change depending on the construction technique, consequently, the use of additives can significantly vary among the different construction techniques.

The first part of this chapter deals with the use of additives for different applications and the optimization of the mixtures for different construction techniques. The second part is dedicated to the issue of soil variability and the influence of mineral composition when using biopolymers. The third part of the chapter deals with issues of results comparability between different studies and the last part discusses the problem of biodegradability when using natural additives.

2.1 Optimization of mixtures with natural additives for different applications

The main characteristics of mixture preparation and final dry density depend on the manufacturing by compaction or by molding, and on the addition of fibers into the mix. The different phases of the sample preparation are thus interdependent and every step of the process influences the final result. The dry density presents higher values for compacted than for molded samples. This is due to the air expulsed during compression and to different initial water content that, when drying, creates voids and low density. In both cases, the addition of the fibers reduces the dry density due to the lower density of fibers and the possible change in volume of fibers when drying, which creates additional voids in the structure. Using compaction, the higher the compaction effort, the higher is the density [16], [89], [90]. As Moevous et al. [91] assess, the initial water content is within the plastic range for PL and AD, to ensure workability, with values around 15-30% for the majority of the analyzed studies [8], [28], [35], [38], [42], [47]–[49], [53], [66], [67], [86]. The lowest values are for CEB and RE, around 10-20% for [11], [15], [16], [33], [34], [39], [46], [54], [58], [60], [61], [70]. Moreover, the water demand can be significantly increased with fiber addition and this behavior is remarkable when different amounts of fiber addition are tested [35], [46], [47]. As an example, the use of 0 or 2 wt% of corn pith for plaster preparation can increase the water demand from 17 to 57% [46].

Among the analyzed research, fiber addition was present in all the studies on PL and 80% for AD and CEB techniques, while it is almost absent in RE. This different use of fibers is due to the final application with different final requirements. Fibers are suitable for plasters because of their function of reducing shrinkage and density at the same time, consequently reducing thermal conductivity. The reduction of the density is less suitable for techniques such as AD, CEB, and RE because it can lead to lower mechanical resistance, which is a crucial aspect for load-bearing material, but not for plasters. Moreover, the use of fibers requires a higher initial water content that is not suitable for the CEB and RE compaction process, because the voids in the matrix are full of water that can reduce the final density when dried and thus the mechanical resistance. Because of this reason, sand is often used to reduce shrinkage avoiding the problems of lower dry density. Sand content can be optimized in combination with fibers addition to improve a specific material property for its final application [41]. The optimum, in this case, is given by a combination of two different factors (e.g. best percentage of sand and fibers addition). A different option is testing one or more material properties to identify which additives percentage is the best one [43], [92]. As an example, Emiroğlu et al. [93] tested the optimum clay/sand ratio considering the compressive strength and shrinkage test result together. These options are quite demanding but can ensure the optimization of the specific combination of soil-grading-additives for a particular application. In the case of RE and ST, liquid or powders biopolymers are mainly used, such as gums, cow blood, lignin, sodium caseinate, and oils, probably to avoid the reduction of dry density often caused by fibers, and the consequent increase of initial water content. This consideration is valid excluding the most common use of chemical additives that are generally used for RE, ST and CEB often in combination with fibers [11], [14]–[16], [44].

2.2 Soil variability and natural additives suitability

As underlined by several of the analyzed studies, the mineral clay composition of the soil affects its interactions with the additives. Consequently, it influences the additive suitability and the optimum quantity to be used for a specific application [55], [56], [60], [61], [86]. As an example, Sorgho et al. [61] and Keita et al. [60] assessed that the presence of iron minerals in soil stabilized with tannins is responsible for the increased compressive strength due to the formation of tannin macromolecular complexes with iron minerals. Similar analyses have been done on xanthan gum using different kinds of clay [55], [83]. The mineral composition is thus an important variable to anticipate the efficiency of stabilization

The impact of composition has been analyzed only in a limited number of studies among the cross-section considered, and further research should be encouraged in this direction. To assess the effectiveness of one specific additive, a wide range of tests with different clay typologies could be necessary. An additional problem is that in many studies there is a lack of information about the soil composition, such as the grain size distribution. Consequently, it is difficult to interpret the results to identify possible suitable combinations of soil composition and specific additives to use with. This consideration underlines the already mentioned difficulty of working with a non-standardized material, that shows wide variability in the mineral clay composition as well as in the grain size distribution. To conclude, the suitability of the additives must be tested beforehand for each new soil or clay typology, before being used in a real application, while waiting for new research correlating the suitability of the additives for different soil compositions.

2.3 Issues of comparability between different research of additives' effects

The comparisons of different results from the analyzed literature is not always straightforward, due to the high number of variables that can influence the results of a test. First, the samples' preparation technique has very high variability, due to different equipment available in the laboratory that hosts the research. For example, among the analyzed studies, it was possible to find, for the same technique of construction, a wide range of samples' sizes and shapes. Principally a parallelepiped or cube are used for CEB and AD, to test the properties of such modular piece. The cylinder is more commonly used for RE and ST, following the typical geotechnical guidelines. These differences can influence the results of the test for the mechanical properties, as illustrated by Aubert et al. [94]. Moreover, the samples for CEB or RE are prepared with a specific compaction effort (CE), an additional parameter that impacts the final physical properties, increasing the density and the mechanical resistance [90]. Among the analyzed studies the compaction energy can vary from 2 to 20 MPa. Moreover, the compaction can be static or applied by a pneumatic hammer for bigger samples, leading to differences in physical properties. As an example, Mansour et al. [89] analyzed the effect of the compaction effort variation, finding that the bulk density varied from 1607 kg/m^3 to 2194 kg/m^3 when the applied compacting pressure rose from 0.39 MPa to 3.16 MPa. As a result, the observed mechanical resistance of the material rose from 0,35 MPa to 4 MPa, and the thermal conductivity increased from 0.618 to 1.483 W/m K. Therefore, when sample preparation involved both additives and a compaction process, the comparison with results presented in other studies should be evaluated considering the contribution of the compaction effort. Isolate the contribution of this factor is possible within the same study if appropriated control samples are prepared and tested. Moreover, the drying conditions before the test can additionally influence the material properties, due to the hygroscopic behavior of the material. Finally, the test conditions (e.g. compressive test speed, experimental setup) can vary and influence the final result. A future adoption of a common framework for test procedures could help to overcome this problem. It is specifically important for the durability studies that can include a large variability in the experimental setup [95]–[98]. To conclude, the evaluation of the additives' effect is significant only if compared with the control samples within the same study, while the comparison between different studies is often problematic. Indeed, when the contributions of several factors are combined, the comparison of absolute values is not recommended. The comparison of the increased or decreased performances as relative values can be meaningful when only one additive is present in a study or when additives are analyzed independently. In this way, it is possible to overcome the problems related to different procedures for sample preparation, test procedure and drying conditions. However, the already mentioned issue of soil variability and its possible influence on the results should also be considered. In addition, precise characteristics of each component should be reported in the studies, including clay minerals, grain size distribution of the soil and of the additive when relevant (fibers and particles), etc. Future research on a common datasheet is highly recommended.

2.4 Biological vulnerability and sanitizing agents

The addition of organic materials into a clay matrix could generate sanitary problems related to fungal growth or insect parasite attack, particularly in high humidity conditions [99]. Only 2 studies over 50 handle this matter [8], [48]. Giroudon et al. [48] tested the use of lavender and barley straws, a by-product reaching about 15.000 tons/year in France. Lavender straw mixture gave better results than barley straw in terms of fungal growth resistance, probably thanks to the particular chemical composition of the lavender. Polyphenols and aroma substances can have positive and antioxidant activities, antimicrobial and anti-pest properties. Santos et al. [8] tested the biological susceptibility to molds using a bio degradant agent fungal culture of A. niger with a test period of four weeks at 22 ± 1 C and 70± 5% RH. The results of the test showed that the addition of a low quantity of lime (0.02 wt%) with natural fibers reduced significantly the A. niger growth due to the increased pH, while the lime addition had a negative impact in terms of capillary absorption and mechanical properties.

3 Conclusions and new possibilities of research

As shown in the present review, the use of natural additives, wastes, and recycled materials is a new frontier in the raw earth stabilization research, that can also take advantage of the studies on soil stabilization with biopolymers. The lack of management of new waste and by-products can create several environmental issues. Consequently, evaluating their suitability as bio-building construction materials contributes to the reduction of raw materials consumption and cost of disposal of waste and by-products.

The use of the additives changes with the different construction techniques, to suit sample preparation and manufacturing process. The final dry density presents higher values when the material is mechanically compacted than when it is cast in a formwork, mainly because of the air removed by the compaction process; in both cases, the use of fibers reduces the final dry density due to the lower fiber's density but the high presence of sand and gravel has the opposite effect due to its high specific gravity. Fiber addition is suitable for reducing shrinkage and improving hygrothermal properties, consequently, the highest quantity of fiber addition is used for PL. Moreover, fiber addition generates different responses in mechanical performances and durability, depending on the quantity of addition, the length and the properties of the fibers. Among the analyzed studies, fiber addition is present in all the analyzed studies on PL and 80% for AD and CEB techniques, while it is almost absent in RE. Differently, liquid and powder biopolymers are preferred for CEB, RE, and ST mixtures, to maintain the high density necessary for load-bearing material, and to enhance mechanical resistance and durability.

Biopolymers bind together the particles and modify ductility, plasticity, viscosity, hydrophobicity and cohesion of the earth. Although for some biopolymers the study of the interaction between additives and earth has already shown good advancement, it still requires further investigations, to fully understand the modifications at the microscopic level. The stabilization changes the density and the porosity of the material, influencing mechanical strength, durability, and hygrothermal properties. The main goal of using additives is to find the right mix that achieves a good compromise among the different properties, which can be reached by combining fibers reinforcement with other biopolymers. As an example, a good proportion of fibers could improve the ductility and hygrothermal properties, while the addition of liquid or powders biopolymers contributes to increase cohesion, mechanical resistance and durability. As a result, it can be very difficult to isolate the effect of the single additive with respect to the others. This is the first issue that arises when comparing the results of different studies, followed by the influence of the compaction effort and the drying conditions during the sample preparation. Another issue is the variability of the test conditions, which is combined with all the other factors and influences the final result. The use of shared frameworks and guidelines in experimental procedures and in data reporting is strongly advised to increase the comparability of different studies. As a result, it is recommended to compare only the relative increment of performances against the control samples, always considering that the variability in the clay minerals can influence the interaction with the additive.

Testing each new additive and soil combination in advance is desirable because several studies showed that the stabilizer's efficiency is related to the earth's composition. The complete analysis and characterization of clay minerals are advised to allow full comprehension of the possible interactions with the biopolymers and their efficiency for different soils, which are non-standardized and heterogeneous materials. Similarly, a separate characterization of the additive is advised to facilitate the comprehension of its interactions with the soil and the comparison of the biopolymer with different studies that use similar stabilizers.

For future research, the possibilities of studying different biopolymers can take inspiration from ST field. As an example, few studies consider biopolymers for RE stabilization and the similarities with ST field can suggest their suitability to improve the durability and mechanical strength for RE construction, enlarging the investigation on the hygrothermal properties of the stabilized materials. The combination of different fibers and other biopolymers seems to be an interesting alternative improving at the same time different material properties and avoiding side effects of chemical stabilizers. The relationship of fibers properties and their effects on the mechanical performance would require deeper investigations, using a specific cross-section of studies that evaluated both the fibers characteristics and the properties of the mixture accurately, information often missing in the analyzed studied. More investigations are still required for a full comprehension of the interactions between clay and biopolymers, with particular attention on the influence of different clay minerals during the process. Finally, the risk of biological vulnerability using biodegradable additives requires more investigations, to assess the safety and the durability for long-term use of the building.

Acknowledgments

This review has been realized thanks to the scholarship financially supported by the French program Make Our Planet Great Again and the University Savoie Mont Blanc, in collaboration with the Politecnico di Milano.

4 Bibliography

[1] GlobalABC, UNEP, and IEA, “2018 Global Status Report: towards a zero-emission, efficient and resilient buildings and construction sector,” p. 73, 2018, doi: 978-3-9818911-3-3.

[2] P. Villoria Sáez and M. Osmani, “A diagnosis of construction and demolition waste generation and recovery practice in the European Union,” *J. Clean. Prod.*, vol. 241, 2019, doi: 10.1016/j.jclepro.2019.118400.

[3] P. Melià, G. Ruggieri, S. Sabbadini, and G. Dotelli, “Environmental impacts of natural and conventional building materials: A case study on earth plasters,” *J. Clean. Prod.*, vol. 80, pp. 179–186, 2014, doi: 10.1016/j.jclepro.2014.05.073.

[4] G. Minke, *Building with earth*. Walter de Gruyter, 2012.

[5] H. Danso, B. Martinson, M. Ali, and C. Mant, “Performance characteristics of enhanced soil blocks: A quantitative review,” *Build. Res. Inf.*, vol. 43, no. 2, pp. 253–262, 2015, doi: 10.1080/09613218.2014.933293.

[6] A. Arrigoni, R. Pelosato, G. Dotelli, C. T. S. Beckett, and D. Ciancio, “Weathering’s beneficial effect on waste-stabilised rammed earth: a chemical and microstructural investigation,” *Constr. Build. Mater.*, vol. 140, pp. 157–166, 2017, doi: 10.1016/j.conbuildmat.2017.02.009.

[7] R. Eires, A. Camões, and S. Jalali, “Enhancing water resistance of earthen buildings with quicklime and oil,” *J. Clean. Prod.*, vol. 142, pp. 3281–3292, 2017, doi: 10.1016/j.jclepro.2016.10.141.

[8] T. Santos, L. Nunes, and P. Faria, “Production of eco-efficient earth-based plasters: Influence of composition on physical performance and bio-susceptibility,” *J. Clean. Prod.*, vol. 167, pp. 55–67, 2017, doi: 10.1016/j.jclepro.2017.08.131.

[9] A. E. Losini *et al.*, “Evaluation of different raw earthen plasters stabilized with lime for bio-building exploitation,” Jun. 2019. doi: 10.26168/icbbm2019.25.

[10] J. L. Parracha, A. S. Silva, M. Cotrim, and P. Faria, “Mineralogical and microstructural characterisation of rammed earth and earthen mortars from 12th century Paderne Castle,” *J. Cult. Herit.*, vol. 42, pp. 226–239, Mar. 2020, doi: 10.1016/j.culher.2019.07.021.

[11] I. Alam, A. Naseer, and A. A. Shah, “Economical stabilization of clay for earth buildings construction in rainy and flood prone areas,” *Construction and Building Materials*, vol. 77. pp. 154–159, 2015, doi: https://doi.org/10.1016/j.conbuildmat.2014.12.046.

[12] S. Burroughs, “Recommendations for the Selection, Stabilization, and Compaction of Soil for Rammed Earth Wall Construction,” *J. Green Build.*, vol. 5, no. 1, pp. 101–114, Feb. 2010, doi: 10.3992/jgb.5.1.101.

[13] P. Zak, T. Ashour, A. Korjenic, S. Korjenic, and W. Wu, “The influence of natural reinforcement fibers, gypsum and cement on compressive strength of earth bricks materials,” *Constr. Build. Mater.*, vol. 106, pp. 179–188, 2016, doi: 10.1016/j.conbuildmat.2015.12.031.

[14] C.-M. Chan, “Effect of natural fibres inclusion in clay bricks: Physico-mechanical properties,” *Int. J. Civ. Environ. Eng.*, vol. 3, no. 1, pp. 51–57, 2011.

[15] M. Mostafa and N. Uddin, “Experimental analysis of Compressed Earth Block (CEB) with banana fibers resisting flexural and compression forces,” *Case Stud. Constr. Mater.*, vol. 5, pp. 53–63, 2016, doi: 10.1016/j.cscm.2016.07.001.

[16] B. Taallah, A. Guettala, S. Guettala, and A. Kriker, “Mechanical properties and hygroscopicity behavior of compressed earth block filled by date palm fibers,” *Construction and Building Materials*, vol. 59. pp. 161–168, 2014, doi: https://doi.org/10.1016/j.conbuildmat.2014.02.058.

[17] S. Burroughs, “Soil property criteria for rammed earth stabilization,” *J. Mater. Civ. Eng.*, vol. 20, no. 3, pp. 264–273, 2008, doi: 10.1061/(ASCE)0899-1561(2008)20:3(264).

[18] D. Ciancio, C. T. S. Beckett, and J. A. H. Carraro, “Optimum lime content identification for lime-stabilised rammed earth,” *Construction and Building Materials*, vol. 53. pp. 59–65, 2014, doi: https://doi.org/10.1016/j.conbuildmat.2013.11.077.

[19] R. Bahar, M. Benazzoug, and S. Kenai, “Performance of compacted cement-stabilised soil,” *Cem. Concr. Compos.*, vol. 26, no. 7, pp. 811–820, 2004, doi: 10.1016/j.cemconcomp.2004.01.003.

[20] S. Deboucha and R. Hashim, “A review on bricks and stabilized compressed earth blocks,” *Scientific Research and Essays*, vol. 6, no. 3. pp. 499–506, 2011, doi: 10.5897/SRE09.356.

[21] B. V. Venkatarama Reddy and P. Prasanna Kumar, “Embodied energy in cement stabilised rammed

earth walls," *Energy Build.*, vol. 42, no. 3, pp. 380–385, Mar. 2010, doi: 10.1016/j.enbuild.2009.10.005.

[22] F. Pacheco-Torgal and S. Jalali, "Earth construction: Lessons from the past for future eco-efficient construction," *Construction and Building Materials*, vol. 29. Elsevier Ltd, pp. 512–519, 2012, doi: 10.1016/j.conbuildmat.2011.10.054.

[23] A. Arrigoni *et al.*, "Reduction of rammed earth's hygroscopic performance under stabilisation: an experimental investigation," *Build. Environ.*, vol. 115, pp. 358–367, 2017, doi: 10.1016/j.buildenv.2017.01.034.

[24] M. Saidi, A. S. Cherif, B. Zeghmati, and E. Sediki, "Stabilization effects on the thermal conductivity and sorption behavior of earth bricks," *Constr. Build. Mater.*, vol. 167, pp. 566–577, 2018.

[25] R. Anger and L. Fontaine, "Bâtir en terre: du grain de sable à l'architecture," *Bâtir en terre du grain sable à l'architecture*, p. 223, 2009.

[26] D. V. Ribeiro, T., Oliveira and S. Bracci, "The Use of Contact Sponge Method to Measure Water Absorption in Earthen Heritage Treated with Water Repellents," *Int. J. Archit. Heritage, 1-12.*, 2020, doi: 10.1080/15583058.2020.1751344.

[27] A. Vissac, A. Bourgès, D. Gandreau, R. Anger, and L. Fontaine, *Argiles & Biopolymères*. 2017.

[28] R. Aguilar *et al.*, "The potential use of chitosan as a biopolymer additive for enhanced mechanical properties and water resistance of earthen construction," vol. 114, pp. 625–637, 2016, doi: 10.1016/j.conbuildmat.2016.03.218.

[29] J. L. Parracha, A. S. Pereira, R. Velez da Silva, N. Almeida, and P. Faria, "Efficacy of iron-based bioproducts as surface biotreatment for earth-based plastering mortars," *Journal of Cleaner Production*, vol. 237. 2019, doi: 10.1016/j.jclepro.2019.117803.

[30] C. Cocozza, A. Parente, C. Zaccone, C. Mininni, P. Santamaria, and T. Miano, "Comparative management of offshore posidonia residues: Composting vs. energy recovery," *Waste Manag.*, vol. 31, no. 1, pp. 78–84, Jan. 2011, doi: 10.1016/j.wasman.2010.08.016.

[31] F. Jové-Sandoval, M. M. Barbero-Barrera, and N. Flores Medina, "Assessment of the mechanical performance of three varieties of pine needles as natural reinforcement of adobe," *Constr. Build. Mater.*, vol. 187, pp. 205–213, 2018, doi: 10.1016/j.conbuildmat.2018.07.187.

[32] M. Maddison, T. T. Mauring, K. Kirsimäe, and Ü. Mander, "The humidity buffer capacity of clay–sand plaster filled with phytomass from treatment wetlands," *Build. Environ.*, vol. 44, no. 9, pp. 1864–1868, 2009, doi: 10.1016/j.buildenv.2008.12.008.

[33] Y. Millogo, J. E. Aubert, E. Hamard, and J. C. Morel, "How properties of kenaf fibers from Burkina Faso contribute to the reinforcement of earth blocks," *Materials (Basel).*, vol. 8, no. 5, pp. 2332–2345, 2015, doi: 10.3390/ma8052332.

[34] Y. Millogo, J. C. Morel, J. E. Aubert, and K. Ghavami, "Experimental analysis of Pressed Adobe Blocks reinforced with Hibiscus cannabinus fibers," *Constr. Build. Mater.*, vol. 52, pp. 71–78, 2014, doi: 10.1016/j.conbuildmat.2013.10.094.

[35] J. Lima and P. Faria, "Eco-efficient earthen plasters: The influence of the addition of natural fibers," in *RILEM Bookseries*, 2016, vol. 12, pp. 315–327, doi: 10.1007/978-94-017-7515-1_24.

[36] A. A. R. Corrêa, L. M. Mendes, N. P. Barbosa, T. De Paula Protásio, N. De Aguiar Campos, and G. H. D. Tonoli, "Incorporation of bamboo particles and 'synthetic termite saliva' in adobes," *Constr. Build. Mater.*, vol. 98, pp. 250–256, Nov. 2015, doi: 10.1016/j.conbuildmat.2015.06.009.

[37] A. A. R. Corrêa, T. D. P. Protásio, J. T. De Lima, G. D. Tomoli, and L. M. Mendes, "Mechanical properties of adobe made with sugar cane Bagasse and 'synthetic termite saliva' incorporation," in *Key Engineering Materials*, 2015, vol. 634, no. December 2014, pp. 351–356, doi: 10.4028/www.scientific.net/KEM.634.351.

[38] Y. Brouard, N. Belayachi, D. Hoxha, N. Ranganathan, and S. Méo, "Mechanical and hygrothermal behavior of clay – Sunflower (Helianthus annuus) and rape straw (Brassica napus) plaster bio-composites for building insulation," *Constr. Build. Mater.*, vol. 161, pp. 196–207, 2018, doi: 10.1016/j.conbuildmat.2017.11.140.

[39] H. Danso, D. B. Martinson, M. Ali, and J. B. Williams, "Physical, mechanical and durability properties of soil building blocks reinforced with natural fibres," *Constr. Build. Mater.*, vol. 101, pp. 797–809, 2015, doi: 10.1016/j.conbuildmat.2015.10.069.

[40] M. C. N. Villamizar, V. S. Araque, C. A. R. Reyes, and R. S. Silva, "Effect of the addition of coal-ash and

cassava peels on the engineering properties of compressed earth blocks," *Constr. Build. Mater.*, vol. 36, pp. 276–286, 2012, doi: 10.1016/j.conbuildmat.2012.04.056.

[41] S. Serrano, C. Barreneche, and L. F. Cabeza, "Use of by-products as additives in adobe bricks: Mechanical properties characterisation," *Constr. Build. Mater.*, vol. 108, pp. 105–111, 2016, doi: 10.1016/j.conbuildmat.2016.01.044.

[42] A. V. Oskouei, M. Afzali, and M. Madadipour, "Experimental investigation on mud bricks reinforced with natural additives under compressive and tensile tests," *Constr. Build. Mater.*, vol. 142, pp. 137–147, 2017, doi: 10.1016/j.conbuildmat.2017.03.065.

[43] T. Ashour, A. Bahnasawey, and W. Wu, "Compressive strength of fibre reinforced earth plasters for straw bale buildings," vol. 1, no. 3, pp. 86–92, 2010.

[44] T. Ashour, A. Korjenic, S. Korjenic, and W. Wu, "Thermal conductivity of unfired earth bricks reinforced by agricultural wastes with cement and gypsum," *Energy Build.*, vol. 104, pp. 139–146, 2015, doi: https://doi.org/10.1016/j.enbuild.2015.07.016.

[45] D. Statuto, C. Sica, and P. Picuno, "Experimental development of clay bricks reinforced with agricultural by-products.," *Actual Tasks Agric. Eng.*, no. February, 2018.

[46] M. Palumbo, F. McGregor, A. Heath, and P. Walker, "The influence of two crop by-products on the hygrothermal properties of earth plasters," *Build. Environ.*, vol. 105, pp. 245–252, 2016, doi: 10.1016/j.buildenv.2016.06.004.

[47] F. Stazi, A. Nacci, F. Tittarelli, E. Pasqualini, and P. Munafò, "An experimental study on earth plasters for earthen building protection: The effects of different admixtures and surface treatments," *Journal of Cultural Heritage*, vol. 17. pp. 27–41, 2016, doi: https://doi.org/10.1016/j.culher.2015.07.009.

[48] M. Giroudon, A. Laborel-Préneron, J. E. Aubert, and C. Magniont, "Comparison of barley and lavender straws as bioaggregates in earth bricks," *Constr. Build. Mater.*, vol. 202, pp. 254–265, 2019, doi: 10.1016/j.conbuildmat.2018.12.126.

[49] E. Olacia, A. L. Pisello, V. Chiodo, S. Maisano, A. Frazzica, and L. F. Cabeza, "Use of seagrass fibres in adobe bricks," in *IOP Conference Series: Earth and Environmental Science*, 2019, vol. 225, no. 1, doi: 10.1088/1755-1315/225/1/012051.

[50] S. Liuzzi *et al.*, "Hygrothermal properties of clayey plasters with olive fibers," vol. 158, pp. 24–32, 2018.

[51] M. F. Attom and M. M. Al-sharif, "Soil stabilization with burned olive waste," no. March 1997, 1998.

[52] M. Achenza and L. Fenu, "On Earth Stabilization with Natural Polymers for Earth Masonry Construction," *Mater. Struct.*, vol. 39, no. 1, pp. 21–27, 2006, doi: 10.1617/s11527-005-9000-0.

[53] J. Nakamatsu, S. Kim, J. Ayarza, E. Ramírez, M. Elgegren, and R. Aguilar, "Eco-friendly modification of earthen construction with carrageenan: Water durability and mechanical assessment," *Construction and Building Materials*, vol. 139. pp. 193–202, 2017, doi: https://doi.org/10.1016/j.conbuildmat.2017.02.062.

[54] S. Muguda *et al.*, "Mechanical properties of biopolymer-stabilised soil-based construction materials," *Géotechnique Lett.*, vol. 7, no. 4, pp. 309–314, 2017, doi: 10.1680/jgele.17.00081.

[55] N. Latifi *et al.*, "Improvement of Problematic Soils with Biopolymer — An Environmentally Friendly Soil Stabilizer," vol. 29, no. 2, pp. 1–11, 2017, doi: 10.1061/(ASCE)MT.1943-5533.0001706.

[56] I. Chang, J. Im, A. K. Prasidhi, and G. C. Cho, "Effects of Xanthan gum biopolymer on soil strengthening," *Constr. Build. Mater.*, vol. 74, no. x, pp. 65–72, 2015, doi: 10.1016/j.conbuildmat.2014.10.026.

[57] I. Chang, A. K. Prasidhi, J. Im, and G.-C. Cho, "Soil strengthening using thermo-gelation biopolymers," *Construction and Building Materials*, vol. 77. pp. 430–438, 2015, doi: https://doi.org/10.1016/j.conbuildmat.2014.12.116.

[58] C. Galán-Marín, C. Rivera-Gómez, and J. Petric, "Clay-based composite stabilized with natural polymer and fibre," *Constr. Build. Mater.*, vol. 24, no. 8, pp. 1462–1468, 2010, doi: 10.1016/j.conbuildmat.2010.01.008.

[59] A. Perrot, D. Rangeard, and E. Courteille, "3D printing of earth-based materials: Processing aspects," *Construction and Building Materials*, vol. 172. pp. 670–676, 2018, doi: https://doi.org/10.1016/j.conbuildmat.2018.04.017.

[60] I. Keita *et al.*, "Ageing of clay and clay-tannin geomaterials for building," *Constr. Build. Mater.*, vol. 61, pp. 114–119, 2014, doi: 10.1016/j.conbuildmat.2014.03.005.

[61] B. Sorgho *et al.*, “Strength and creep behavior of geomaterials for building with tannin addition,” pp. 937–946, 2014, doi: 10.1617/s11527-013-0104-7.

[62] Q. Chen and B. Indraratna, “Deformation Behavior of Lignosulfonate-Treated Sandy Silt under Cyclic Loading,” *J. Geotech. Geoenvironmental Eng.*, vol. 141, no. 1, p. 06014015, Jan. 2015, doi: 10.1061/(ASCE)GT.1943-5606.0001210.

[63] B. Ta’negonbadi and R. Noorzad, “Stabilization of clayey soil using lignosulfonate,” *Transp. Geotech.*, vol. 12, pp. 45–55, 2017, doi: 10.1016/j.trgeo.2017.08.004.

[64] T. Zhang, G. Cai, and S. Liu, “Application of lignin-based by-product stabilized silty soil in highway subgrade : A fi eld investigation,” *J. Clean. Prod.*, vol. 142, pp. 4243–4257, 2017, doi: 10.1016/j.jclepro.2016.12.002.

[65] G. Cai, T. Zhang, S. Liu, J. Li, and D. Jie, “Stabilization Mechanism and Effect Evaluation of Stabilized Silt with Lignin Based on Laboratory Data,” *Mar. Georesources Geotechnol.*, vol. 34, no. 4, pp. 331–340, 2016, doi: 10.1080/1064119X.2014.966217.

[66] G. Araya-Letelier, J. Concha-Riedel, F. C. Antico, C. Valdés, and G. Cáceres, “Influence of natural fiber dosage and length on adobe mixes damage-mechanical behavior,” *Constr. Build. Mater.*, vol. 174, pp. 645–655, 2018, doi: 10.1016/j.conbuildmat.2018.04.151.

[67] F. Aymerich, L. Fenu, and P. Meloni, “Effect of reinforcing wool fibres on fracture and energy absorption properties of an earthen material,” *Constr. Build. Mater.*, vol. 27, no. 1, pp. 66–72, 2012, doi: 10.1016/j.conbuildmat.2011.08.008.

[68] H. Fatehi, S. M. Abtahi, H. Hashemolhosseini, and S. M. Hejazi, “A novel study on using protein based biopolymers in soil strengthening,” *Constr. Build. Mater.*, vol. 167, pp. 813–821, 2018, doi: 10.1016/j.conbuildmat.2018.02.028.

[69] Y. Millogo, J. E. Aubert, A. D. Séré, A. Fabbri, and J. C. Morel, “Earth blocks stabilized by cow-dung,” *Mater. Struct. Constr.*, vol. 49, no. 11, pp. 4583–4594, 2016, doi: 10.1617/s11527-016-0808-6.

[70] C. Kraus, D. Hirmas, and J. Roberts, “Compressive strength of blood stabilized earthen architecture,” in *Earthen Architecture: Past, Present and Future*, 2014, pp. 217–220, doi: 10.1201/b17392.

[71] F. Champiré, A. Fabbri, J.-C. Morel, H. Wong, and F. McGregor, “Impact of relative humidity on the mechanical behavior of compacted earth as a building material,” *Construction and Building Materials*, vol. 110. pp. 70–78, 2016, doi: https://doi.org/10.1016/j.conbuildmat.2016.01.027.

[72] P. Chauhan, A. El Hajjar, N. Prime, and O. Plé, “Unsaturated behavior of rammed earth: Experimentation towards numerical modelling,” *Constr. Build. Mater.*, vol. 227, p. 116646, 2019, doi: 10.1016/j.conbuildmat.2019.08.027.

[73] C. T. Vendrusculo, J. L. Pereira, and A. R. P. Scamparini, “Gellan Gum: Production And Properties,” in *Food Hydrocolloids*, Springer US, 1994, pp. 91–95.

[74] A. Palaniraj and V. Jayaraman, “Production, recovery and applications of xanthan gum by Xanthomonas campestris,” 2011, doi: 10.1016/j.jfoodeng.2011.03.035.

[75] S. M. Viswanath, D. Gallipoli, and A. W. Bruno, “Geotechnical characterisation of recycled biopolymer- stabilised earthen materials Caractérisation géotechnique de matériaux de terre recyclés stabilisés,” no. September, 2019, doi: 10.32075/17ECSMGE-2019-0164.

[76] S. Hotchkiss, K. Philp, A. Trius, M. Brooks, and R. Campbell, *The use of carrageenan in food THE USE OF CARRAGEENAN IN FOOD Complimentary Contributor Copy*. 2016.

[77] I. D. Hay, Z. U. Rehman, M. F. Moradali, Y. Wang, and B. H. A. Rehm, “Microbial alginate production, modification and its applications,” *Microb. Biotechnol.*, vol. 6, no. 6, p. n/a-n/a, Sep. 2013, doi: 10.1111/1751-7915.12076.

[78] Valerio Carlucci, “An interview with the CEO of World’s Advanced Saving Project Massimo Moret,” *Technol. all*, pp. 24–27, 2016.

[79] A. Perrot, D. Rangeard, F. Menasria, and S. Guihéneuf, “Strategies for optimizing the mechanical strengths of raw earth-based mortars,” *Constr. Build. Mater.*, vol. 167, pp. 496–504, 2018.

[80] S. Banakinao, S. Tiem, K. Lolo, Y. Koutsawa, and K.-S. Bedja, “Dataset of the use of tannin of néré (parkia-biglobosa) as a solution for the sustainability of the soil constructions in West Africa,” *Data in Brief*, vol. 8. pp. 474–483, 2016, doi: https://doi.org/10.1016/j.dib.2016.05.072.

[81] D. Zimbardi, P., Cardinale, G., Demichele, M., Nanna, F., Viggiano, D., Bonini, C., ... & Tofani, “Lignin recovery. A resource to value; La lignina: una risorsa da valorizzare.,” 1999.

[82] B. Indraratna and M. A. Al Mahamud, “Stabilisation of an erodible soil using a chemical admixture,”

Proc. Inst. Civ. Eng. Gr. Improv., vol. 163, no. 1, pp. 43–51, 2010, doi: 10.1680/grim.2010.163.1.43.

[83] I. Chang, M. Jeon, and G. C. Cho, "Application of microbial biopolymers as an alternative construction binder for earth buildings in underdeveloped countries," *Int. J. Polym. Sci.*, vol. 2015, 2015, doi: 10.1155/2015/326745.

[84] H. Danso, D. B. Martinson, M. Ali, and J. Williams, "Effect of fibre aspect ratio on mechanical properties of soil building blocks," *Constr. Build. Mater.*, vol. 83, pp. 314–319, 2015, doi: 10.1016/j.conbuildmat.2015.03.039.

[85] A. Laborel-Préneron, J. E. Aubert, C. Magniont, C. Tribout, and A. Bertron, "Plant aggregates and fibers in earth construction materials: A review," *Construction and Building Materials*, vol. 111. pp. 719–734, 2016, doi: https://doi.org/10.1016/j.conbuildmat.2016.02.119.

[86] L. Randazzo, G. Montana, A. Hein, A. Castiglia, G. Rodonò, and D. I. Donato, "Moisture absorption, thermal conductivity and noise mitigation of clay based plasters: The influence of mineralogical and textural characteristics," *Appl. Clay Sci.*, vol. 132–133, pp. 498–507, 2016, doi: 10.1016/j.clay.2016.07.021.

[87] C. Rode, "Moisture Buffering of Building Materials Department of Civil Engineering Technical University of Denmark," 2005.

[88] A. Antunes, P. Faria, V. Silva, and A. Brás, "Rice husk-earth based composites: A novel bio-based panel for buildings refurbishment," *Constr. Build. Mater.*, vol. 221, pp. 99–108, 2019, doi: 10.1016/j.conbuildmat.2019.06.074.

[89] M. Ben Mansour, A. Jelidi, A. S. Cherif, and S. Ben Jabrallah, "Optimizing thermal and mechanical performance of compressed earth blocks (CEB)," *Constr. Build. Mater.*, vol. 104, pp. 44–51, 2016, doi: 10.1016/j.conbuildmat.2015.12.024.

[90] A. W. Bruno, D. Gallipoli, C. Perlot, and J. Mendes, "Mechanical behaviour of hypercompacted earth for building construction," *Mater. Struct. Constr.*, vol. 50, no. 2, 2017, doi: 10.1617/s11527-017-1027-5.

[91] M. Moevus, R. Anger, and L. Fontaine, "Hygro-Thermo-Mechanical Properties of Earthen Materials for Construction : a Literature Review," *Terra 2012*, pp. 1–10, 2012.

[92] S. Liuzzi, C. Rubino, and P. Stefanizzi, "Use of clay and olive pruning waste for building materials with high hygrothermal performances," in *Energy Procedia*, Sep. 2017, vol. 126, pp. 234–241, doi: 10.1016/j.egypro.2017.08.145.

[93] M. Emiroğlu, A. Yalama, and Y. Erdoğdu, "Performance of ready-mixed clay plasters produced with different clay/sand ratios," *Appl. Clay Sci.*, vol. 115, pp. 221–229, Oct. 2015, doi: 10.1016/j.clay.2015.08.005.

[94] J. E. Aubert, A. Fabbri, J. C. Morel, and P. Maillard, "An earth block with a compressive strength higher than 45 MPa!," *Constr. Build. Mater.*, vol. 47, pp. 366–369, 2013, doi: 10.1016/j.conbuildmat.2013.05.068.

[95] C. T. S. Beckett, P. A. Jaquin, and J. C. Morel, "Weathering the storm: A framework to assess the resistance of earthen structures to water damage," *Constr. Build. Mater.*, vol. 242, May 2020, doi: 10.1016/j.conbuildmat.2020.118098.

[96] C. T. S. Beckett, C. E. Augarde, D. Easton, and T. Easton, "Strength characterisation of soil-based construction materials," *Geotechnique*, vol. 68, no. 5, pp. 400–409, 2018, doi: 10.1680/jgeot.16.P.288.

[97] P. Gerard, M. Mahdad, A. Robert McCormack, and B. François, "A unified failure criterion for unstabilized rammed earth materials upon varying relative humidity conditions," *Constr. Build. Mater.*, vol. 95, pp. 437–447, 2015, doi: 10.1016/j.conbuildmat.2015.07.100.

[98] B. Medvey and G. Dobszay, "Durability of Stabilized Earthen Constructions: A Review," *Geotechnical and Geological Engineering*. Springer, 2020, doi: 10.1007/s10706-020-01208-6.

[99] M. Z. Levy *et al.*, "Periurban Trypanosoma cruzi-infected Triatoma infestans, Arequipa, Peru," *Emerg. Infect. Dis.*, vol. 12, no. 9, pp. 1345–1352, 2006, doi: 10.3201/eid1209.051662.