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## Plant aggregates and fibers in earth construction materials: a review

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### **Abstract**

Earth as a building material is increasingly being studied for its low environmental impact and its availability. Plant aggregates and fibers have been incorporated into the earth matrix in the aim of enhancing performance for thousands of years but scientific studies began quite recently. The present paper reviews the state of the art of research on the influence of these various natural and renewable resources in unfired earth materials such as compressed earth blocks, plasters, and extruded and stabilized blocks. This review, based on 50 major studies, includes characterization of the particles and treatments, and recapitulative tables of the material compositions, and the physical, mechanical, hygrothermal and durability performances of earth-based materials. A lack of references on hygroscopic and durability properties was observed. Future research orientations are thus suggested to promote and develop this type of sustainable material, which provides a solution for saving energy and natural resources.

### **Highlights**

- Earth-based products with plant aggregates as a sustainable material are reviewed.
- Physicochemical and mechanical properties of plant aggregates or fibers are reviewed.
- Mechanical, hygrothermal and durability performances of the composites are reviewed.
- Further investigations are needed to promote these materials.

### **Keywords**

Earthen construction materials, plant aggregates and fibers, characterization, performances, blocks, plasters.

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## **1 Introduction**

The impacts of buildings on the environment and on the health of their occupants have now become priority issues. Indoor air quality is considered as a major risk factor for human health and improving the environmental quality of buildings has become a major objective, which could be attained by improving their hygrothermal performance and by using safe construction materials with low impact. For many reasons (heritage, ecological, economic, proximity ...), construction materials that have been used by Human for thousands of years, such as earth and/or bio-based materials (wood, fiber and plant aggregates) are being reconsidered as pertinent materials. Earth is still the most widely used construction material in many countries in the world. Even today, around one third of human beings live in earthen houses and, in developing countries, this figure is more than one half [1]. In advanced economies, earth construction was abandoned in favor of concrete for several decades after the Second World War but earth is again becoming attractive nowadays because of its low environmental impact and because it is known to be a natural humidity regulator and to improve comfort inside buildings. It is usual to strengthen and/or to lighten the earthen construction materials by adding plant aggregates. This review results from the bibliographic survey realized prior to the BIOTERRA research project, which aims to characterize the mechanical and hygrothermal properties of building materials (blocks and plasters) composed of earth and bio-based aggregates. The project started in 2014 and is supported by the French National Research Agency. The consortium is composed of 9 French partners (5 laboratories, a technical center and three industrial partners).

The growing interest in traditional earth building has led to numerous publications during the past ten years, mainly on compressed earth blocks and rammed earth buildings, including two recent reviews. Pachego-Torgal and Jalali have written a review on the environmental benefits of earth for future eco-efficient construction [2] and Danso et al. have studied the enhancement of soil blocks in a quantitative review [3]. However, the paper by Danso et al. focused on the effect of binder (chemical or organic) and aggregate or fiber additions on the properties of earth blocks, and only a small part of it concerns plant or animal aggregates or fibers. Furthermore, the systematic use of chemical binders to stabilize earth blocks is open to debate [4].

The review presented here deals with the plant aggregates and fibers used in earth construction materials in general (blocks, earth plasters, rammed-earth, cob and wattle and daub). It is based on 50 published studies of earth-based composites with plant aggregates and also includes an analysis of 8 more works on some of the natural fibers found in the initial 50 studies. The review is separated into three parts. The first presents the plant aggregates used in earth construction materials (origins, characteristics and treatments used to improve performance). In the second part, the compositions and the manufacture of earth-based composites are presented. In this part, the subsections correspond to the technique used (earth blocks, earth plasters and a last part grouping rammed earth, cob, and wattle and daub). The third and last part of the paper is composed of 4 sections that present the effects of plant aggregates on the properties of earth-based composites. The four types of properties studied are: physical properties (density, shrinkage, water absorption and sound insulation), mechanical properties (compressive strength and elastic modulus, tensile and flexural strength, and adhesion between earth plasters and wall), hygrothermal properties (vapor permeability, sorption-desorption and thermal conductivity) and durability (resistance to water, resistance to wind-driven erosion, resistance to freezing/thawing, biodegradation and microorganism development).

## **2 Plant aggregates and fibers used in earth construction materials**

### **2.1 Origins and characteristics of plant aggregates and fibers**

Studies of many kinds of bio-aggregates according to the location, and hence the availability, of the materials can be found in the literature. The origin of these bio-aggregates can be plant or animal, but plant products are found in the majority of cases. Only two references concern studies of an animal aggregate, which was sheep wool. Thus, the term employed in this review to refer to bio-aggregates is plant aggregates or fibers as discussed further below. Some plant aggregates or fibers have been used in several studies, others are more original. It is nevertheless possible to group them into eight categories (presented by increasing order of use in the references): cereal straws, wood aggregates, bast fibers, palm tree fibers, waste and residues, leaf fibers, aquatic plant fibers and chips, and sheep wool. In that follows, general information about the origin and manufacture of each category is presented. As mentioned in the introduction, eight additional references, which deal with plant aggregates alone, have been included to complete the review. In order to distinguish these references, the rows of the tables concerning them are shaded.

#### *Cereal straws (17/50)*

This aggregate was studied in 16 of the 50 references. The straw used was from wheat, barley or oats, but this is not always specified. Straw is an agricultural by-product and is the part of cereal's stem rejected during the harvest. Wheat is an annual plant, ranking 3<sup>rd</sup> for global production after rice and corn. Its straw has a hollow, cylindrical structure. Barley, like oat, can be harvested once or twice a year. However, barley can grow in extreme climates, such as in the tropics or on mountains, whereas oat prefers cool temperate climates.

#### *Wood aggregates (10/50)*

These aggregates are always industrial waste from the wood processing industry (joiner's workshop) [5] or by-products of chemical pulping processes [6]. Wood is a ligneous plant used as fiber, chips, sawdust or fine branches. It is able to regulate hygrothermy and provide good thermal insulation [7].

#### *Bast fibers (8/50)*

Bast fibers are extracted from the outside of the stem of cultivated or even wild plants. They have high tensile strength [8] and good thermal insulation property [9]. The fibers are located in the phloem so they must be separated from the woody core by a mechanical and/or retting process. The use of fibers from hemp, flax, jute, kenaf and diss, a Mediterranean wild plant, is reported in the literature. Hemp hurds constitute the by-product of the hemp defibration process and correspond to the lignin-rich part of the stem. They have been used in two cases of study.

#### *Palm tree fibers (7/50)*

Palm trees grow in tropical and subtropical regions or in a warm temperate climate. In this review, three palm fibers are studied. Fibers from coconut husks, called coir, are particularly present in the Philippines, Indonesia, India and Brazil. Degradation of coir is quite slow due to its high lignin content [10]. Fibers from oil palm fruit bunches are also studied in two articles and come from Malaysia [11] or Ghana [12]. Lastly, only one reference deals with the use of date palm fibers (from southern Algeria) [13].

#### *Waste and residues (7/50)*

Some agribusiness wastes or by-products, e.g. from millet, cotton, tea, tobacco, cassava peels or grass, are considered to be no longer useful. They are stocked and abandoned, sometimes

causing environmental problems or health hazards (for example, cassava peel degradation can develop hydrocyanic acid, which is very toxic for humans [14]). Using these low-cost, light materials in construction material is an interesting valorization.

#### *Leaf fibers (5/50)*

The fibers studied were extracted from the leaves of three different plants: sisal, banana and pineapple. All of them are tropical plants, which can be produced in Brazil, Indonesia or Eastern Africa [15] but also in some European Islands as Madeira and Azores.

#### *Aquatic plant fibers and chips (4/50)*

Some of the fibers studied came from aquatic plants, like the well-known seaweeds [16]. Typha (cattail) and phragmites (reed) are common plants used for wastewater treatment. Wastewater passes through wetlands in order to be treated before being released into the natural environment. This kind of aquatic plant can remove some pollutants, such as nitrogen or phosphorus, from the wastewater. They also provide a substrate for the growth of microorganisms able to degrade organic matter. In addition to this ecological function, they are harvested in a semi-natural wetland in Estonia to be used as a raw material for construction (insulation blocks or fiber-wool) [17].

#### *Sheep wool (2/50)*

Unlike cellulose-based fibers, sheep wool is an animal fiber and contains keratin. Protein fibers have poor resistance to alkalis, present in all concretes, which explains the small number of studies. In Aymerich et al. [18], wool was from black and white Sardinian sheep. The use of this wool is very limited in the textile industry, thus it is already used in thermal and acoustic insulation of buildings. Unprocessed wool from Scotland was studied in Galán-Marín et al. [19].

The plant aggregates and fibers were all incorporated into the earth matrix and most of the properties of the composites will be presented in the following parts of the review. In order to better understand these results, the detailed characteristics of the different plant aggregates and fibers studied in the literature are given below.

Physical, chemical and mechanical characteristics are presented in Table 1 and Table 2. In Table 1, dedicated to the physical characteristics, all the 50 references are considered, yielding 27 kinds of plant aggregates and fibers grouped in 8 families. The physical characteristics presented are: the length, the diameter, the apparent density, the absolute density, the water absorption and the thermal conductivity. Some references do not give any physical characteristics, as can be seen in this table. This was also the case for chemical and mechanical characteristics (composition, elastic modulus, and tensile strength) and Table 2 quotes only the references presenting these characteristics. It can also be noted that, of the 50 references used in this review, only 4 present both the chemical composition and mechanical characteristics (flax fibers [8], kenaf fibers [20], coir [21] and sisal fibers [22]). Moreover, little mention is made of the chemical and mechanical characteristics of plant aggregates and fibers in the references concerning earth material. In Table 2, partial information is provided by only 6 of the 50 references.

Table 1: Physical properties of plant materials used in earth construction materials

Type		Length (cm)	Diameter (mm)	Apparent density (kg.m <sup>-3</sup> )	Absolute density (kg.m <sup>-3</sup> )	Absorption (%)	Thermal conductivity (mW.m <sup>-1</sup> .K <sup>-1</sup> )	Reference
Cereal straw	Wheat straw	1.5 – 2.5	0.5					[23]
		5		103.6			41.4 – 48.6	[24,25]
		5	3					[26]
		0 - 3		33	868	280 - 350		[27]
								[28]
	Barley straw	5		106.9				[24,25]
		1 - 6	1 - 4		2050	500 - 600		[29]
		0.5 - 2		47	870	400		[27]
	Oat straw	1 - 2						[30,31]
	Straw		2 - 5					[32]
		20 - 30						[33]
		5	3					[34]
		5						[35]
							[36–40]	
Wood aggregates	Wood (shavings or fibers)	2						[5]
		2		111.4			35.3 – 53.9	[24,25]
		0.3 – 0.8						[41]
				50	440	240		[42]
			0.025-0.05					[6]
						[6,7,39,43, 44]		
Bast fibers	Hemp fiber	0.85 – 1.7						[45]
			0.035					[8]
					1500	80 - 105		[21]
	Hemp hurds	0.5 – 3.5	1 - 8			280		[46]
		2	2 - 5					[47]
	Flax fiber	7 – 8.5						[48]
			0.013					[8]
	Jute fiber	2 - 4	1		1700			[49]
				1460			[50]	
Kenaf fiber	3	0.13		1040	307		[20,51]	
Diss fiber	2						[52]	
Palm tree fibers	Coir		2.38				78	[53]
		3.5 - 5	0.35					[54]
		5	0.27			100		[15]
					1177	145		[21]
								[55]
	Oil palm fiber	1						[11]
								[12]
Date palm fiber	2 – 3.5	0.1 – 0.8	512 - 1089	1300 - 1350	97 - 203		[13]	
Waste and residues	Cassava peel	5	5					[14]
	Millet residue				1164			[56,57]
	Cotton residue	0.01			500			[58]
	Tea residue							[59]
	Tobacco residue		0.025-0.05					[6]

	Grass		0.025-0.05					[6]
Leaf fibers	Sisal fiber	5	0.15			230		[15]
		4 - 5						[60]
		4	0.15					[47]
		7.2	0.3			1370		[22]
		45 - 160	0.004 – 0.012			1370	110	[50]
	Banana fiber	0.85 – 1.7					[45]	
	Pineapple fiber	1					[11]	
Aquatic plant	Phragmite	2	2					[17]
	Typha	2	2					[17]
								[31]
	Seaweed fiber	1						[16]
Wool	Sheep wool	1, 2, 3	0.035					[18]
								[19]

Table 1 shows that a great diversity of plant components can be used in earth blocks. It can be seen that their length varies greatly, from 0 to 30 cm, with a large majority of cases between 1 and 5 cm. This length has to be compared with the size of the sample. The longest particles, straw between 20 and 30 cm, were used in a cob wall, the size of which was 80 x 70 x 110 cm<sup>3</sup>. This wall was, however, sawed into segments of 42 x 42 x 11.5 cm<sup>3</sup>, which were used for the different experiments [33]. Particle lengths were sometimes chosen in relation with the specimen size to keep mixing uniform. For instance, fibers from pineapple leaves and oil palm fruit bunches in Chee-Ming [11] were 1/10 of the length of the block specimen. Sisal fibers in Sen and Reddy [50], having lengths between 45 and 160 cm are not taken into account because the article concerns the fiber alone, not incorporated into an earth matrix.

A first glance at the table shows that the variation in diameter is also considerable, from 0.004 to 8 mm. However, the diameter of fibers cannot be compared to that of shavings. It is also important to note that fibers form a bundle at first, but they are generally used separated from one another. Some of the reported values may be for fibers in bundle form, such as the jute fibers 1 mm in diameter in Güllü and Khudir [49]. Confusion between the two forms of fibers is often due to the difficulty of isolating an elementary fiber.

In order to distinguish the different types/families of plant particles (fibers, aggregates or straw), two geometrical dimensions are represented in Figure 1: the inverse of the aspect ratio (1/AR), which is the ratio of the length to the diameter, versus the diameter. It is noticeable that fibers present the smallest 1/AR and diameter and the aggregates have the highest 1/AR (higher than 0.10). Straw particle ARs are between the other two, but their diameter can be similar to those of fibers or aggregates.

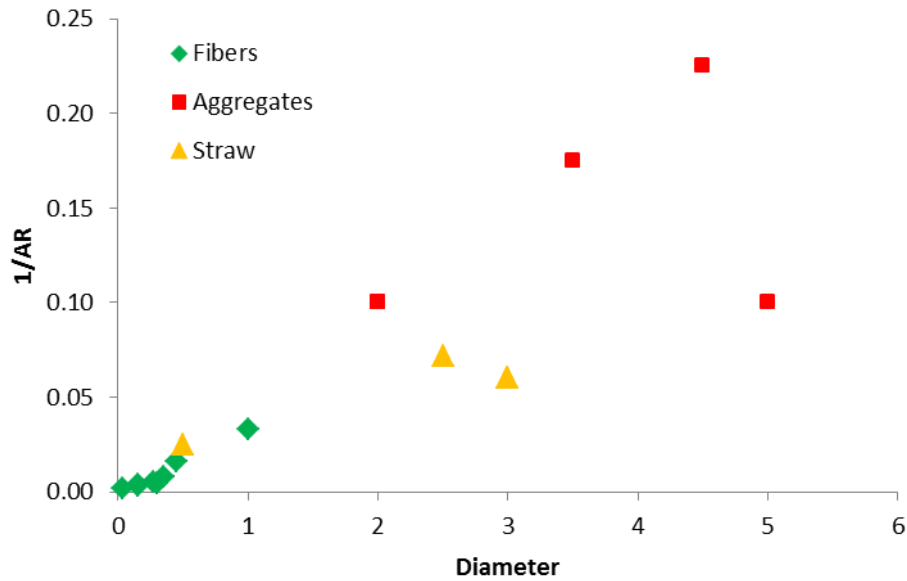


Figure 1: Aspect ratio of the particle versus its diameter

A huge diversity of plant aggregate and fiber shapes can therefore be added to an earth matrix, with distinct objectives. For instance, to reduce shrinkage cracking (especially in plasters), the use of plant particles in fiber form is preferable. In this case, the fiber length will play an important role in the non-propagation of cracks. However, when the aim is to reduce the weight of the composite material, and so increase thermal or acoustic insulation for example, the shape of the plant aggregate has a lower impact. The diameter of aggregates is larger than the one of fibers (Figure 1).

The apparent density can vary by a factor of three for the same plant particle. However, details of the procedures used to measure this property are not always provided in the literature, which could explain such differences. The definition of the density is quite confused: is it the bulk density of the particles or the apparent density of the particle itself? In the first case, knowledge of this characteristic does not seem very useful to predict the properties of the mixtures of earth and plant particles as the bulk arrangement of plant aggregates or fibers will be modified when they are introduced into the mixture. The only interest of such a characteristic could be linked to the transport of these plant aggregates or fibers but, in this case too, it is possible to compact them, thus changing this property again. It is also possible to observe significant differences in the absolute densities of a given plant particle (see the case of barley straw for example) but it is difficult to generalize this observation because this characteristic is rarely given for the plant aggregates and fibers studied.

For the majority of plant aggregates and fibers, the water absorption is significant (higher than 100%). This property is very interesting because it would provide composites with a high ability to regulate the humidity of the indoor air in the buildings. In the same way, the thermal conductivity of the plant aggregates and fibers is very low, ranging between 35 and 80  $\text{mW}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ , and these aggregates could also be considered as insulating materials. Thus they could improve the thermal properties of earthen materials at the same time as their hygroscopic properties.



Table 2: Chemical and mechanical properties of plant particles used in earth construction materials

Type	Composition (%)			Elastic modulus (GPa)	Tensile strength (MPa)	Reference
	Cellulose	Lignin	Hemicellulose			
Hemp fiber	64	4	16			[9]
				21	1077	[8]
				34	900	[21]
Wood aggregates	50	16-33	7-29			[6]
Flax fiber (Harakeke)	61	8	27	21	805	[8]
	81	3	14			[61]
	60	3	16			[9]
Jute fiber	72	13	13			[61]
				10-30	400-800	[50]
Kenaf fiber	70	19	3	136	1000	[20]
Diss fiber					100	[52]
Coir	43	46	0.25			[53]
				3	150	[15]
	41	27	22		144	[61]
	21	47	12	10-40	73-505	[21]
Oil palm fiber	49	23	21			[61]
Date palm fiber				5	233	[13]
Sisal fiber				18	580	[15]
	65.8	9.9	12	15.5	472	[22]
				15	363	[50]
	73	11	13	15	347-378	[21]
Banana fiber	26	25	17			[21]

For the characteristics presented in Table 2, although some differences exist, the values obtained for a given plant aggregate or fiber are more homogeneous than those of Table 1. It is noteworthy that the only mechanical property previously studied in the literature is the tensile strength of some fibers, because fibers are used as flexural reinforcement. However, for some other applications, including plant aggregates such as wood shavings or hemp hurds, it could be relevant to assess the compressive behavior of plant particles. Hemp fibers have the highest elastic modulus and tensile strength. The other fibers could be ranked by decreasing tensile strength: flax, jute, sisal, date palm and coir. It is interesting to note that coir has the highest lignin content and the lowest tensile strength. Moreover, it seems that there is a link between the cellulose content and the mechanical characteristics of fibers, as suggested by Millogo et al. [20].

## 2.2 Aggregate and fiber treatments used for earth composites

Treatments could be useful to improve some characteristics and properties of natural aggregates and fibers for their use in earth materials. Alkaline treatment, acetylation, hydrothermal treatment and water-repellent coating were studied in ten references. In one case, aggregates were treated for health reasons: cassava peels were dried in the sun for three days to eliminate hydrocyanic acid (HCN), which is very toxic for humans [14]. The other impacts of the treatments are described below and summarized in Table 3.

### 2.2.1 Water absorption and dimensional variations of the aggregates and fibers

As shown in Table 1, natural aggregates and fibers can absorb significant amounts of water, often more than 100%. Their dimensions can also vary according to their moisture content,

and vary greatly during drying of the sample. Plant aggregates and fibers are hydrophilic materials that absorb manufacturing water. This absorption by the particles can be avoided for good dimensional stability. The bigger the dimensional variation is, the lower is the binding with the matrix. Limiting water absorption is thus often desirable.

A water repellent can be applied to the aggregates or fibers. It may be enamel paint (spray or immersion), a mix of rosin and alcohol, bitumen or acrylic coating [48]. Coir and sisal fibers were treated with two kinds of bitumen coating called “ciplá” and “piche” [15]. The “piche” repellent was more effective than the “ciplá”. With this treatment, water absorption of sisal was about 30% lower than that of coir, whereas non-treated sisal was more absorbent (230% for sisal, only 100% for coir). It seems that sisal fibers were more porous than coir, so they could absorb the water-repellent more easily.

Other treatments, such as acetylation, were tested to change the morphology of the aggregates or fibers and thus to decrease their water absorption [22]. Acetylation is a chemical reaction that replaces OH groups by others that are more voluminous and have less affinity with water. Alkaline treatment was less effective than acetylation [22] because the fiber structure was more dense after it. The treatment engendered a decrease in the fiber diameter.

Three other effective treatments were tested on wood shavings in Ledhem et al. [42]: immersion in boiling water, in linseed oil and in boiling water with lime. During the immersion, the water-soluble substances were extracted. These substances can cause wood to swell. With the two treatments in boiling water, it appeared that the reduction of dimensional variation was greater than the water absorption. The best result was obtained with linseed oil, after which the water absorption by wood shavings was 42%, instead of 112% with boiling water treatment, 89% in boiling water with lime and 240% without treatment.

### **2.2.2 Mechanical properties of aggregates or fibers and composites**

The effects of treatments on the mechanical properties of the fibers could be positive or negative. With a coating of enamel paint, fibers were more fragile than without treatment [48].

It was shown that acetylation could have both positive and negative effects. A decrease in tensile strength and elastic modulus was observed by Alvarez et al. [22] whereas Hill et al. [61] found different results. The chemical reaction improved tensile strength when it took place at 100°C but decreased it when performed at 120°C because, at this temperature, the fibers were damaged.

Three different alkaline treatments were tested in Efendy et al. [8] and all of them led to a decrease of up to a 30% in the tensile strength of harakeke and hemp fibers. This is explained by the decrease of the fiber diameters due to the treatment. Young’s modulus of hemp fibers was increased with the three treatments but was not really modified in harakeke. The improvement for hemp may have been due to an increase in cellulose rigidity induced by the removal of non-cellulosic components. Flexural modulus was improved by 20% with a 48-h alkaline treatment at 25°C [22].

Boiling water treatment slightly improved the mechanical performances of the composite material according to Ledhem et al. [42] but decreased the compressive strength and slightly improved the flexural strength in Fertikh et al. [52]. Linseed oil treatments decreased mechanical properties, especially tensile strength [42], by around 11% for the mix with paraffin [54].

### **2.2.3 Aggregate and fiber adhesion to the matrix**

Adhesion of the plant aggregate or fiber to the matrix can be evaluated by a tensile or flexural test: the adhesion is good if no aggregate or fiber debonding is observed, that is to say if the

particle is broken at the end of the test [22]. Adhesion can also be estimated with SEM imaging: the rougher the texture of the fiber, the better its contact with the matrix [8].

Adhesion to the matrix was improved when the fibers were treated by acetylation [22] and treated fibers broke during the mechanical tests whereas the untreated ones slipped relative to the matrix. However, it was shown by Alvarez et al. [22] that a 1h of acetylation reaction improved the adhesion between fiber and matrix, whereas adhesion was decreased if the reaction lasted 24h or 48h.

Alkaline treatment was one of the most common among the references. Fibers were treated to improve adhesion to the matrix, which was one condition for obtaining good mechanical strength of the composite. Alkaline treatment separated fiber bundles in harakeke and hemp. Adhesion between fibers was due to pectin, hemicellulose and lignin, which were removed by the chemical reaction. After the treatment, the fibers were rougher and grooved, which explains the better adhesion to the matrix [8,22]. Another reason for alkaline treatment was to give a homogenous mix between the matrix and cotton waste. The cotton was soaked in a sodium hydrate solution (NaOH) to remove waxes and oil [58].

However, some treatments, such as immersion in boiling water or linseed oil, induced a decrease in adhesion. With immersion in boiling water, some spine fibers were removed, which led to lower fiber-matrix adhesion [52]. With the linseed oil treatment, the adhesion between fibers and a cement-clay matrix decreased as the treatment intensity increased [42].

#### 2.2.4 Durability of the plant aggregates or fibers

Plant aggregates or fibers are organic materials, which are thus subject to natural decomposition that occurs through the centuries [35]. However, the definition of durability varies for different authors. For example, it was shown by Babu and Vasudevan [62] that coir fibers only lasted for 2 to 3 years without any treatment. Some authors tried to improve their durability by various processes.

Acetylation was applied to coir and oil palm fiber in Hill et al. [61]. It was observed that resistance to decay and humidity was improved with this treatment. Both the treated and untreated fibers were put in soil and a tensile test was performed every 4 weeks for 20 weeks. On untreated fibers, it was impossible to measure the tensile strength after 8 weeks because the fibers were too damaged. The tensile strength of treated fibers decreased with exposure, but was still about 80% of the initial value after 20 weeks.

Treatment was also applied to avoid mold development inside the matrix and thus avoid accelerated damage. Mold was observed inside the barley straw, certainly due to storage [27]. To eliminate the mold, fibers were immersed in a saline solution of NaCl and then in an aqueous solution of NaOH.

The immersion of coir in a mix of boiled linseed oil, paraffin and a solvent to coat the fibers was tested in an attempt to improve their durability [54]. According to the author, this kind of water repellent increased the lifetime by 8 to 12 years.

Table 3: Impacts of various treatments on the properties of plant aggregates and fibers (+ when the property is improved, - if not)

Treatment	Coating				Acetylation	Alkaline	Thermal immersion		
	Enamel	Acrylic	Bitumen	Rosin-alcohol			Boiling water	Boiling water with lime	Linseed oil
Reference	[48]	[48]	[15,48]	[48]	[22,61]	[8,22,58]	[42,52]	[42]	[42,54]
Water absorption	+	+	+	+	+	negligible effect	+	+	+

Mechanical properties	-				+ 100°C - 120°C [61] - [22]	+ flexion[22] - tensile[8]	+ [42] - compression + flexion [52]		-
Adhesion					+	+	-		-
Durability					+	+			+

### 3. Compositions and manufacture of earth-based composites

The compositions of earth-based composites are summarized in the following tables (Tables 4 to 8). They are grouped by construction techniques: blocks (adobes, compressed earth blocks, extruded blocks and stabilized blocks), plasters and monolithic walls (rammed earth, cob, wattle and daub). Properties of the soil used to make these materials are presented when available (Atterberg limits (liquid limit wL, plastic limit wP and plasticity index PI), dry density and particle size distribution). The weight percentages of the different types of plant aggregates and fibers are also presented with their respective lengths. Plant aggregate or fiber contents that were expressed by volume in the reference have been converted into weight contents (wt%) when possible (density known) to standardize the units of the data. Some fields were not presented in some articles, so the boxes have been left empty.

#### 3.1 Earth blocks

##### 3.1.1 Unstabilized adobes

Adobes are masonry elements, handmade and molded, and generally dried in the sun. This technique, still used in non-industrialized countries, is very ancient. It was used, for example, to build the city of Shibam in Yemen in the 15<sup>th</sup> century [1].

Table 4 presents the characteristics of the soils and plant materials used in adobes.

Table 4: Characteristics of soils and plant aggregates or fibers used in adobes

Ref.	Soils						Plant aggregates or fibers		
	wL (%)	wP (%)	PI (%)	Clay (%)	Silts (%)	Sand (%)	Type	Length (cm)	Content (wt%)
[32]	23	20	3	60% quartz, 18% illite, 22% vermiculite			straw, fine wood branches		0.23
[54]				9	18	73	Coir	3.5 or 5	0.8 - 3.2
[15]	30	24	6				sisal, coir	5	4
[35]				25			straw	5	0 - 1
[28]	47	16	31	49			wheat straw		1
[51]	38	20	18	25	30	45	hibiscus cannabinus	3 - 6	0.2 - 0.8
[34]	26	18	8	22	50	25	straw	5	0 - 1
[44]				10	5	85	sawdust, cow-dung, molasses		0 - 20 (by volume)
[26]				15	25	60	wheat straw	5	0.7 - 3.8

There are 9 references dealing with studies on adobes mixed with plant aggregates or fibers. For these references, the characteristics of the soil used are not always specified but when they are, strong differences appear: this is the case for Atterberg limits, where the Plasticity Index ranges from 3 to 31%. 7 studies give the mineralogical composition of the soil: in most cases, the percentage of clay corresponds to the particle size analysis (passing below 2  $\mu\text{m}$ ). Finally, in this type of material, the plant aggregate or fiber contents are quite low, ranging from 0.23 to 4% by mass, but this table shows the ability of adobes to be manufactured with large aggregates: most of them are around 5 cm.

### 3.1.2 Unstabilized Compressed Earth Blocks (CEB)

This type of masonry element is a descendant of adobe blocks. Blocks are compacted with a manual or mechanical press. Table 5 presents the characteristics of soils and plant materials used in CEB.

Table 5: Characteristics of soils and plant aggregates or fibers used in CEB

Ref.	Soils						Plant aggregates or fibers		
	w <sub>L</sub> (%)	w <sub>P</sub> (%)	PI (%)	Clay (%)	Silts (%)	Sand (%)	Type	Length (cm)	Content (wt%)
[18]	28	17	11	7	58	35	wool	1, 2 or 3	2 - 3
[56]				lateritic			millet		0 - 12.2
[57]				lateritic			millet		0 - 12.2
[29]	57	23	33				barley straw	1 - 6	0 - 3.5
	33	15	18						
	32	18	14						
	40	22	18						
[46]	33	21	12	19			hemp	0.5 - 3.5	15 - 22
[12]	35	24	11	11	-	-	palm		0 - 1.5

The number of studies of CEB containing plant aggregates or fibers (6 references) is much lower than for adobes. Contrary to what was observed previously with adobes, the characteristics of the soils studied seem a little less dispersed: the plasticity index varies from 11 to 33% and the clay content (based on the particle size distribution) from 7 to 19%. This may be related to the recommendations established in the French standard on CEB [63], which provides some reference values for the particle size distribution and the plasticity index of soils used for the manufacture of CEB. Finally, the most interesting thing in Table 5 is the high percentages of plant aggregates or fibers that could be added in CEB. In some studies, the authors added up to 22% by mass of hemp. Such additions were possible thanks to the CEB manufacturing technique, in which the blocks are pressed and the rheological behavior of the fresh material has little effect, in contrast to the case of extruded blocks, for example.

### 3.1.3 Unstabilized Extruded Earth Blocks (EEB)

Extruded blocks are manufactured with the earth in a plastic state. Generally produced in an industrial process, these blocks can present perforations and are dried in an oven (105°C [59]). Table 6 presents the characteristics of soils and plant materials used in CEB.

Table 6: Characteristics of soils and plant aggregates or fibers used in extruded blocks

Ref.	Soil				Plant aggregates or fibers		
	w <sub>L</sub> (%)	w <sub>P</sub> (%)	PI (%)	Clay (%)	Type	Length (cm)	Content (wt%)
[59]					tea		0 - 5
[6]					sawdust, tobacco, grass		0 - 10
[39]	Claytec brick 7002DF				straw, wood chips		0.2 - 0.8
[7]	48	22	26	20 - 40	wood fiber		

There are few references dealing with the use of plant aggregates or fibers in extruded blocks and those that exist give little data apart from the type and amount of plant aggregates or fibers added. The plant contents are often low, certainly because the process requires the mixture to be sufficiently flowable to pass through a machined die at the outlet of the extruder. Nevertheless, in one study, the content reached 10%. This may have been due to the small size of the aggregates but this characteristic was not given in the article.

### 3.1.4 Stabilized earth blocks

These blocks may be adobes, CEB or manufactured like concrete, by vibro-compaction or pouring into molds. A stabilizer (mineral binder, polymer, etc.) is added to the earth in order to improve the characteristics of the block, such as mechanical properties or durability (resistance to water). Some blocks were dried in the sun [16], others had water sprinkled on them during the curing process (exposed to sunshine for 2-3 weeks, and to air for 1 week) [55] and others were simply stored for 28 days before testing. Table 7 presents the characteristics of the soils and plant materials used in stabilized blocks and their manufacturing techniques.

Table 7: Characteristics of soils and plant aggregates or fibers used in stabilized blocks

Ref.	Soil						Stabilizer/treatment		Plant aggregates or fibers			Technique
	w <sub>L</sub> (%)	w <sub>P</sub> (%)	PI (%)	Clay (%)	Silts (%)	Sand (%)	Type	Content (wt%)	Type	Length (cm)	Content (wt%)	
[16]			3	0.5	51.5	48	beetroot (3/4) and tomato (1/4) polymer	10	seaweed	1	10	Adobe
[5]			12	alluvial aggregate			cement	20	wood aggregate	2	10 - 40	Pouring
[58]				limestone			cement	11	cotton		0 - 6	CEB
[36]							cement lime basaltic pumice gypsum	12.5 2.5 18.7 3.7	straw		2.7	Vibro-compaction
[37]				32	25	43	cement lime basaltic pumice gypsum	10 10 10 10				Vibro-compaction
[38]							cement basaltic pumice gypsum	15 15 15				Vibro-compaction
[41]				kaolinite			cement	25	wood aggregate	0.3 - 0.8	0 - 37.5	Pouring
[11]	46	22	24				cement	0 - 15	pineapple, oil palm fruit bunch	1	0 - 0.75	CEB
[52]							lime		diss	2	6	
[19]	35	19	16	32	45	23	alginate	0 or 25	sheep wool		0 - 0.6	CEB
[49]	37	25	12				lime	0 - 10	jute	2 - 4	0 - 1	CEB
[53]	non-plastic			lateritic		12	cement	11	coir		0 - 2.2	CEB
[42]							cement	0 - 80	wood aggregate		0 - 29	Pouring
[45]	34	28	6	Bayeux quarry fines			cement lime	7 0 or 2	hemp, banana	0.8 - 1.7	0.6	CEB
[43]			15	lateritic			cement	8 or 10	sawdust		0 or 9	CEB
[14]	35	17	18				coal-ash	0 - 10	cassava peel	5	0 - 5	CEB
[55]				11	2	87	cement	7	coconut husk		0 or 1	CEB

[48]				3	20	77	cement	10	harakeke (flax)	7 or 8.5	0.6 or 0.8	Adobe
[13]	36	23	13				cement	0- 8	date palm	2 - 3.5	0 - 0.2	CEB

The references dealing with stabilized blocks containing plant aggregates or fibers are the most numerous (19 references). Several types of binders were used during these studies: cement (with or without mineral additions) was used in 13 out of 19 cases, lime in 5 cases and organic stabilizer in two (alginate, and beetroot and tomato polymer). The size of the plant aggregates or fibers used in stabilized blocks was comparable to that observed in other types of blocks (only flax fibers were a little bit longer (8.5 cm)) but the plant particle content in some blocks could be very significant, especially for wood aggregates: 40% in [5], 37.5% in [41] and 29% in [42]. Such high plant aggregate or fiber contents would certainly lead to significant problems of strength but these seem to have been solved by using high binder content (cement for the references on wood aggregates). However, the amounts of binder used in other references are often very high, which could raise questions on the environmental impact of such materials when cement and/or lime are used. It is important to note that the cement content in concrete blocks is below 7% ( $150 \text{ kg/m}^3$ ) and these blocks are hollow. This means that the comparison with a solid earth block stabilized with cement is even more disadvantageous for the earth block regarding cement content. To date there are still few studies dealing with the use of natural organic stabilizers but this is certainly the most sustainable solution and should be developed in the future.

### 3.2 Earth plasters

Earth plasters are usually applied on masonry walls, wattle and daub or straw bale buildings to protect them. They are composed of clay, water and sometimes plant aggregates or fibers to avoid drying shrinkage but that is not absolutely necessary [64]. Here, none of the plasters studied were stabilized by a mineral binder, which could have improved resistance to rain and abrasion. Table 8 presents the characteristics of the soils and plant materials used in earth plasters.

Table 8: Characteristics of soils and plant aggregates or fibers used in earth plasters

Ref.	Soil						Plant aggregates or fibers		
	w <sub>L</sub> (%)	w <sub>P</sub> (%)	PI (%)	Clay (%)	Silts (%)	Sand (%)	Type	Length (cm)	Content (wt%)
[24,25]				31	22	47	barley and wheat straw (Sw), wood shavings (W)	5 (Sw), 2 (W)	0 - 16.7
[30]							oat	1 - 2	
[47]				26	32	42	sisal (S), hemp chaff (H)	4 (S), 2 (H)	0.5
[17]							wool and chips of typha, chips of phragmite	2	0 - 2
[31]							Oat straw, typha wool		0 - 80 (by volume)

The Atterberg limits of soils are not presented in the references dealing with the use of plant aggregates or fibers in earth plasters but, in general, these soils have a high level of plasticity that enables the plasters to be spread on the wall. The aggregates and fibers used for this type of material were short because of the small thickness applied. Moreover, in general, the particle content was low in order to obtain homogeneous mixtures that were easy to apply to the wall, except in reference [24], where a very high aggregate or fiber content was used.

### **3.3 Rammed earth, cob, wattle and daub**

Other techniques exist, but are not currently studied, especially with plant aggregates or fibers. Rammed earth is a technique that consists in compacting moist earth within a formwork. Cob is a mixture of earth and straw assembled in layers to build a monolithic wall. Wattle and daub is a traditional construction technique with a wood structure.

These traditional earth construction techniques are very little studied in the literature and the few studies found were not very relevant. One concerned the 20-year durability of rammed earth [65] but the results for walls containing straw were not presented. Rammed earth was also studied in Miccoli et al. [33], where the mechanical behavior was compared with that of cob (which is made with 1-2% of straw 20-30 cm in length) and CEB. In Chabriac et al. [66] rammed earth and cob were studied, but their compositions were unknown. Two studies of wattle and daub were found. In Laurent's 1987 study [40], the straw weight content was between 0.5 and 22%. The other [60] studied "bahareque", but as a plaster. This technique, used in tropical countries, is similar to wattle and daub. It consists in applying a soil-fiber mixture to a wood or bamboo structure. The fiber used in the reference was sisal fiber, 4-5 cm in length, with a 1% weight content. The mixture was stabilized with cement or cactus pulp. Another way to build a monolithic wall with very lightweight material is the straw-clay technique. The material studied by Oudhof et al. [67] was composed of earth mixed with water and straw and then compressed in a mold by hand.

## **4. Effects of plant aggregates or fibers on the physical properties of earth-based composites**

### **4.1 Density**

This property is interesting because it can be correlated with many properties of the composite material, such as thermal or mechanical characteristics. As expected, the bulk densities of all the plant aggregates and fibers used in the references studied were lower than that of the soil. Increasing the particle content led to a decrease in the earth content and thus a decrease in the composite dry density [23,53,59]. For instance, a cotton residue content of 40% by volume engendered a 29% decrease in density [58]. Porosity also increased when millet content increased [56]. However, the density decrease was not significant with the addition of oil palm fruit bunch fiber [11], but this could be explained by the low proportion of fiber, less than 1% by weight.

Figure 2 recapitulates the dry bulk densities of the materials studied in the references according to their aggregate or fiber contents by weight. The values are classified according to the manufacturing technique. The global decrease of density with the increase of aggregate or fiber content is well illustrated, although wide dispersion of the values can be noted, especially for the lower particle contents. For example, for an aggregate or fiber content of 10%, the bulk density is between  $1810 \text{ kg.m}^{-3}$  and  $1010 \text{ kg.m}^{-3}$ . Only one value does not follow the trend: a density of  $800 \text{ kg.m}^{-3}$  relative to a particle content of 0.5% [39]. However, this value is easily explainable when the holes of these extruded blocks are taken into consideration.



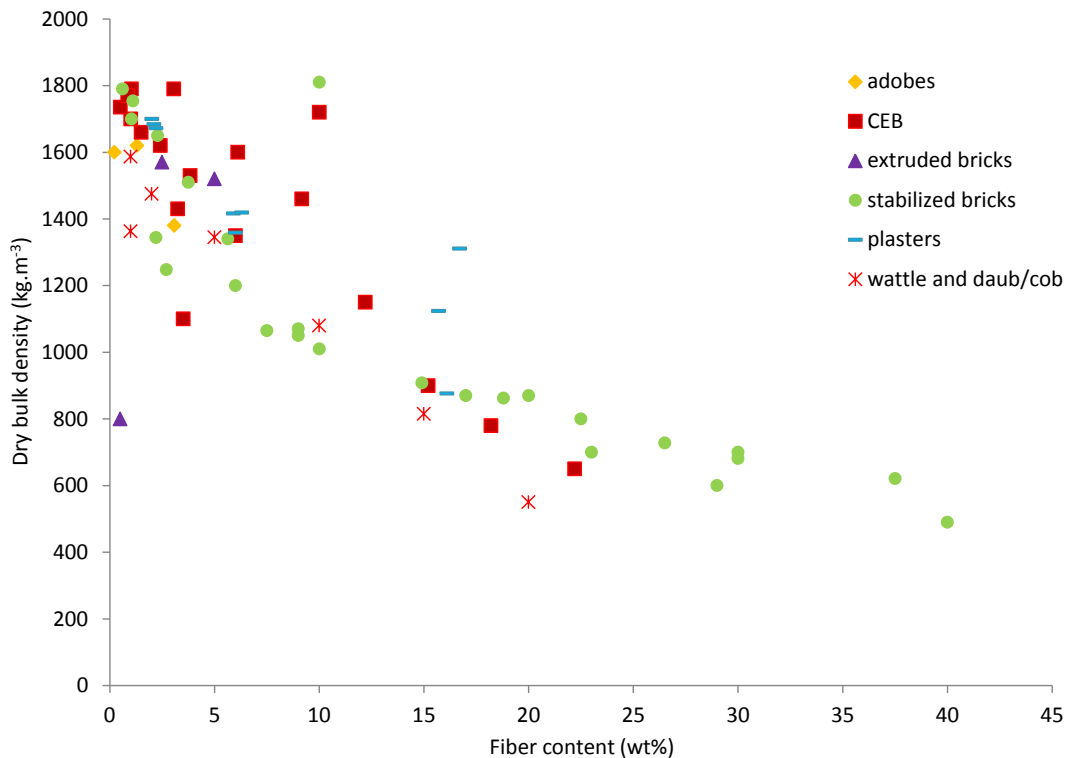


Figure 2: Comparison of the dry bulk density of the different manufacturing techniques according to the aggregate or fiber content values given in the literature.

## 4.2 Shrinkage

Shrinkage is a dimensional variation of the material caused by water evaporation just after manufacture. This volume decrease engenders internal stresses that can lead to shrinkage cracks.

In several studies [15,23,29,47], the addition of plant aggregates or fibers limited cracking as the particles opposed the deformation, thus limiting soil contraction and reinforcing the matrix, in particular for long fibers where adhesion between the fiber and the matrix was better [29]. In Ghavami et al. [15], the optimal length to minimize shrinkage was 5 cm in 4% weight content.

Shrinkage stabilization occurred earlier with the use of straw [29] because of the hollow structure of the stems, which allowed accelerated evaporation.

However, it was observed in Demir et al. [59] that increasing the tea waste content led to greater shrinkage. The authors explained this phenomenon by the increased amount of water needed in the manufacture of the composite, due to the absorbent nature of the aggregate. The use of more than 10% plant residue by weight is not recommended because of the excessive increase of shrinkage cracks engendered [6].

## 4.3 Water absorption

The influence of aggregates or fibers on composite water absorption was very rarely studied, that of stabilizers being much more investigated. Water absorption by the material can be measured by immersion or capillarity. Concerning plasters, absorption is not an indispensable criterion because they are assumed to be inside the building or to be protected from rain [30]. However, it is interesting to measure how they are affected by capillary rise that may occur from the soil. One clear result is that non-stabilized blocks do not resist immersion [11,16]. It is shown in Algin and Turgut [58] that the quantity of water absorbed was proportional to the cotton waste content. Increasing the cotton content by 40% (by volume) more than doubled

the water absorption of the material (from 12.5% to 27.2%) but this value was acceptable in comparison to the other lightweight materials. It was also shown in Taallah et al. [13] that increasing fiber content to 0.2% led to an increase in water absorption and swelling. From these two articles [13,58], it could be generalized that addition of aggregates or fibers increases water absorption because of their high absorption capacity, as shown in Table 1. Moreover, in a study using another absorption test [60], it seemed that water absorption was accelerated by aggregates and fibers.

Water absorption by aggregates and fibers has an important effect on their adhesion with the matrix. Swelling of the particles, engendered by water absorption during the first 24 hours, pushes away the soil. When, after drying, the volume of the particles decreases, voids are created around them, as shown in Figure 3 [15,48].

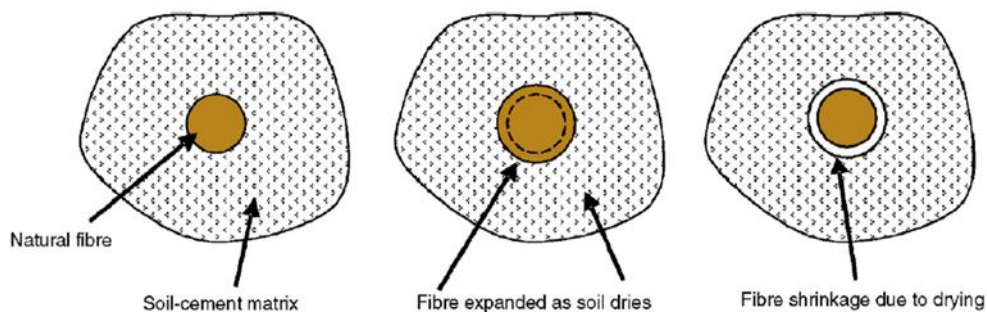


Figure 3: Effect of water absorption on aggregate or fiber adhesion with earth, from [48]

#### 4.4 Sound insulation

Lightweight earth block (with straw for instance) is thought to give a good sound absorption coefficient [1]. However this property has been investigated in only one paper [38]. A measurement to characterize sound insulation of a wall in a small industrial building was performed by Binici et al. [38]. The sound absorption coefficients of three kinds of fibers and 3 stabilizers were compared by the impedance tube method using a sound frequency between 100 and 1800 Hz. Sound absorption coefficients increased with frequency (the opposite of what is observed in concrete and fired bricks). These coefficients were higher with straw than with earth alone, but lower with straw than with plastic fibers or polystyrene. Sound insulation was greater with basaltic pumice than with cement and gypsum.

### 5. Effects of plant aggregates and fibers on the mechanical properties of earth-based composites

These properties are widely studied in all the references, but it is not easy to compare the values measured in a table because each parameter could change: test procedure, sample dimension, type of aggregate or fiber, composition... Therefore, only general trends are described below.

#### 5.1 Compressive strength and elastic modulus

The effect of plant particle additions on compressive strength differed from author to author. In 8 references [6,11,12,19,29,36,51,59], compressive strength was improved by adding aggregates or fibers under different conditions. For example, [29] showed that the strength of the most clayey earth (between 28 and 40% of clay) was improved by 10 to 20% by adding 1.5% of barley straw. For [59], the strength increase was due to the composition of the residues used, which contained other components in addition to cellulose. The addition of pineapple and palm fibers studied in Chee-Ming [11] improved the strength only when the cement weight content was above 15%. Two fibers lengths and different proportions were

studied in Millogo et al. [51]. The optimum determined was a fiber content of 0.4%, which increased the strength by around 16% for short fibers (3 cm) and 8% for the longest fibers (6 cm). This increase of compressive strength was correlated with the characteristics of the plant used. The fiber studied here, *Hibiscus Cannabinus* (or kenaf), showed the highest tensile strength of all the aggregates and fibers investigated (Table 2). Millogo et al. explained that the incorporation of fibers of kenaf reduced the propagation of cracks in the blocks, through the good adherence of fibers to the clay matrix (shown on SEM micrographs), and therefore improved their mechanical properties. Compressive strength was even improved by 37% by sheep wool and was doubled if the wool was combined with alginate [19].

Four other references [7,13,35,45] did not report any influence for plant aggregate or fiber additions. However, this may be explicable by the low aggregate or fiber content (below 1% by weight in the 4 cases).

The compressive strength decreased in 11 references [5,15,23,26,29,34,35,41,42,53,58]. It was found by Algin and Turgut [58] that the dry compressive strength was inversely proportional to the cotton content: a decrease of 71% was reached for an addition of 7% of cotton. When plant particles were added, the dry density was lower and the composite material was more porous [5,15]. Some models linking mechanical properties with porosity were adapted for clay-cement-wood materials and compared with experimental results [41]. Compressive strength decreased with increasing porosity, i.e. increasing wood content. Bal'shin's and Hasselman's models [41] were very close to the experimental results. Moreover, compressive strength was lower with aggregates or fibers because of the weak adhesion between particles and clay matrix [35,53]. The aggregates or fibers could slip easily, reducing the homogeneity of the composite material.

However, no generalization could be made; the influence of aggregates and fibers depended on the type of particle, the soil composition and the testing method. For a given study, using the same soil and the same testing procedures, the addition of palm fibers induced an increase of compressive strength while the addition of pineapple fibers resulted in a decrease [11].

In all cases, ductility was greatly improved with aggregates and fibers, increasing proportionally to their content. There were more cracks but they were less deep [29,35]. This occurred because aggregates, e.g. straw, had a bridging effect with the clay matrix and were more compressible, generating high residual strength. During the rupture of the sample, no particle breaking was observed, only a loss of adhesion with the matrix shown by the debonding of the aggregates. The deformation reached at failure varied considerably depending on the particle type and content: 24% with 0.75% of straw [34], 10% with 4% of coir [15], 13% with 5% of cassava peels [14]. In one case [54], samples containing more than 1.8% of coir fibers never reached failure. Because of their proximity, the fibers could be expected to behave as a mesh, which would lead to the recompression of the earth. When the specimens contained more than 1.8% of fibers, a strain limit of 18% was chosen in order to determine a compressive strength. In Flament [46], the deformation was also large (between 20 and 25%), thus the compressive strength was determined at strains of 1.5 and 7.5% (values inspired by [68]).

The procedure used for the measurement of compressive strength could strongly influence the results because of the specific behavior of earth when it was confined in the compressive strength test [69,70]. The confinement was more marked for earth materials, because of their ductility, and the presence of plant aggregates or fibers, which increased this ductility, increased the effect of confinement during the test. Moreover, because of the high ductility of earth materials having a high plant aggregate or fiber content, there is a problem in the definition of the rupture criteria because, as mentioned before, in some cases of study, the

samples never reached failure. For the moment (and as far as the authors know), no standard takes this specific problem into account.

Young's modulus decreased when natural aggregate or fiber content increased. For example, the highest modulus was 211 MPa for earth alone but it fell to between 100 and 150 MPa with an addition of up to 1% of straw [35]. This Young's modulus reduction was related to the compressive strength by various authors [11,20,27,54]. An empirical model to determine Young's modulus using compressive strength is described in Piattoni et al. [34]. Three theoretical models (Voigt, Reuss and Hill) were there compared and showed good correlation with the experimental results. Other empirical relationships are proposed by Al Rim et al. [5]. The static modulus was calculated from stress-strain graphs and the dynamic modulus, higher, was measured using ultrasonic waves.

## **5.2 Tensile and flexural strength**

Some direct and indirect (Brazilian test) tensile tests were performed. As for compressive strength, tensile strengths varied markedly depending on the reference.

In 5 cases of study, the addition of natural aggregates or fibers decreased the tensile strength [13,26,42,43,54]. For instance, the addition of 0.2% of oil palm fibers led to a decrease of tensile strength of approximately 20% [13]. This could be attributed to the heterogeneity of the material and the fragility and low tensile resistance of the fiber, as can be seen in Table 2. It also could be explained by the decrease of the mineral matrix when it was replaced by sawdust [42] or the weakness of the adhesion between the fibers and the matrix even when there was only 0.6% of fibers [26]. To justify the decrease in tensile strength, [54] assumed that the material was less compacted with the fibers, thus soil particles were less close to each other and cohesion and friction forces were less pronounced.

In 4 other cases of study, tensile strengths were improved by natural aggregate or fiber additions [23,42,45,51]. Tensile strength was improved by 30% with the addition of 1% of wheat straw, which was the particle content leading to the highest dry density [23]. Tensile strength seemed to be influenced by the fiber length for Hibiscus Cannabinus contents of around 0.2% [51]. Ductility was also improved with the addition of fibers, which are able to self-deform a lot, especially when their length increased [51]. Blocks could store elastic energy and were more resistant to crack propagation, an interesting property in case of earthquake [45]. The behavior of the tensile failure was described by Mesbah et al. [71] as a two stage failure: the first one corresponding to the failure of the clay matrix and the second one to that of the aggregate or fiber mesh. Tensile strength was also dependent on the type of particle, its tensile strength and its roughness, which allowed better adhesion to the matrix [27].

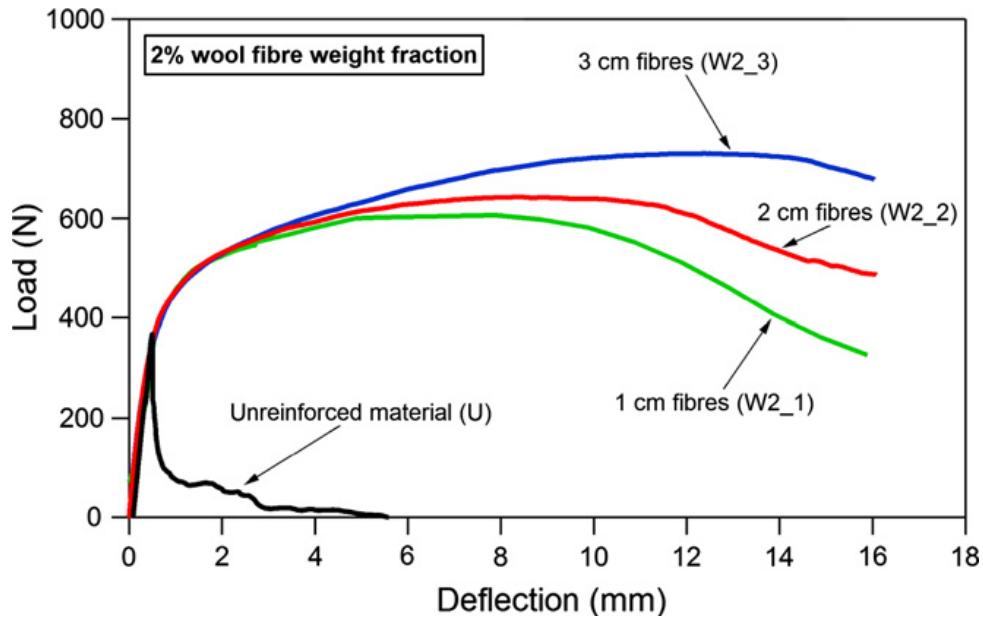


Figure 4: Example of load-deflection curves of unreinforced and reinforced specimens tested by flexion [18]

In 6 references out of 8 [5,18,19,29,46,52], flexural strength was improved by the addition of plant (or sheep wool) aggregates. For instance, flexural strength increased by 30% with an addition of 25% of sheep wool [19]. Crack propagation was limited by the presence of fibers, which led to a bridging effect with the clay and increased the friction at the interface between the fibers and the matrix [18,19]. This was observed specifically for soil containing a lot of clay and for the longest fibers [29]. The link with the length could be explained by a higher contact surface with the clay matrix, and thus better anchorage of the fibers [18]. A relation between flexural and compressive strengths ( $R_f$  and  $R_c$  respectively) was found by Al Rim et al. [5], which was  $R_f = k(R_c)^n$ . Ductility was also greatly improved by fibers, due to their high tensile strength [15]. The behavior of samples containing wool fibers is given in Figure 4 [18]. Fibered samples had an elevated residual strength and more, but smaller, cracks [29]. Deformation was only 3.5% for an earth sample whereas it was about 20% for an earth sample with diss [52]. In only two cases was a decrease of flexural strength found (with the addition of cotton waste [58] and cassava peels [14]).

### 5.3 Adhesion between coating and wall

The mechanical strength of earth plasters was measured in [47] and [30] by testing the adhesion between the plaster and the wall. Different coating formulations were studied to obtain the best adhesion. The strength was determined by applying a mass that was increased by 0.5 kg every 30 seconds. No standardized test exists. Shear resistance improved with an increasing clay content until shrinkage cracks became too severe. The optimal clay content was around 6%. Shrinkage cracks were reduced by adding sisal fibers or, to a lesser extent, by adding hemp hurds, but there were too few results to observe a significant effect on adhesion with the matrix. However, shear strength depended on the wall on which the plaster was applied. For example, the plaster adhered twice as strongly when the wall was made of rammed earth rather than cob [47].

## 6. Hygrothermal properties

### 6.1 Water vapor permeability

The water vapor permeability property has been very little studied for bio-based earth materials. [30] and [67] are the only references in which measurement of the permeability of a

fibered earth material is described. In Faria et al. [30] a water vapor resistance factor  $\mu$  of 8 was found for the wet cup method but the effect of aggregates or fibers was not investigated. In the case of straw-clay mixture [67], which contained much more plant aggregate and was lighter, the water vapor resistance factor was lower: around 3 with the wet cup method and around 5 with the dry cup. However, it was demonstrated that earth had a higher permeability than most building materials [72], although the addition of a stabilizer could change this behavior. In the German standard on earth blocks [73], the use of a standard range between 5 and 10 is suggested, which is in accordance with the values measured on non-fibered earth blocks [74–76].

## 6.2 Sorption-desorption

Porous materials can absorb a certain quantity of the humidity contained in the ambient air and desorb more or less the same quantity. Unfired earth is known for its high capacity to balance air humidity; it is a good water buffer. Moisture absorption is 50 times higher for unbaked blocks than for bricks fired at high temperature [1]. However, only four references that focused on plasters studied this property on earth with plant aggregate or fiber, [17,25,30,31]. This sorption and desorption property can be considered as static or dynamic. For the static property, it has been shown that earth plaster moisture content increases when the ambient relative humidity increases and decreases when ambient temperature increases, but with a smaller effect. Plasters reinforced by barley or wheat straw and wood shavings show a higher absorption rate (up to 6.5% for barley straw) than earth alone (up to 1.7%) [25]. Sorption isotherms were also studied on different straws not combined with earth by Bouasker et al. [27] and showed similar behavior for sorption. For desorption, the decrease in water content of barley straw occurred at a lower relative humidity than for the other straws. However, the moisture content of a plaster is in permanent dynamic equilibrium with the environment. A sudden increment of relative humidity showed a dynamic Moisture Buffer Value (MBV) that rose from 50% to 80% with fibered plasters in [17,31]. According to [31], plasters containing 2% of typha chips absorbed  $38 \text{ g}\cdot\text{m}^{-2}$  of water whereas the same plaster without typha absorbed  $30 \text{ g}\cdot\text{m}^{-2}$  and a gypsum wallboard absorbed only  $10 \text{ g}\cdot\text{m}^{-2}$ . The plasters studied by [31] belong to the higher adsorption class defined in the German Standard DIN 18947 [77], with a value higher than  $60\text{g}\cdot\text{m}^{-2}$  after 12 hours, but no differences were observed between the different type and proportion of aggregates or fibers. All the humidity absorbed was desorbed by the samples after 12h [17,30]. Nevertheless, the moisture sorption was lower with 2% of typha wool than without, and it was this aggregate which gave the higher density reduction. All the natural aggregates and fibers presented by Minke [1] permitted an improvement of the water absorption by the material, which increased with the particle weight content. 2% coconut fibers were the most efficient, followed by 2% cellulose fibers, 3% sawdust, 1% coconut fibers, 2% wheat straw and 3% cement (higher humidity sorption after 15 hours). But, generally speaking, humidity regulation is very rapid due to the high permeability of earth material [76].

## 6.3 Thermal conductivity

Heating and cooling energy can be saved by using material with low thermal conductivity for building. Thermal properties were studied in 13 of the 50 references; it is a common property for building material. Small buildings made of fibered earth blocks were 53.3% cooler in summer than buildings using basaltic pumice blocks and 41.5% warmer in winter [37]. The earthen material allowed 69% savings of heating energy in winter and 57% savings of cooling energy in summer.

It has frequently been shown [5,24,42,51,53,78,79] that an increase in aggregate or fiber content leads to a decrease of thermal conductivity. For instance, the value decreased from

0.24 to 0.008 W.m<sup>-1</sup>.K<sup>-1</sup> for a rise in the proportion of wood shavings from 10 to 50% [5]. This evolution could be linked with the composite density and porosity, and a linear relation between thermal conductivity ( $\lambda$ ) and density (d) was found in [5]:  $\lambda = 0.228d - 0.006$ . Earlier, the empirical model determined by [40] was:  $\lambda_{dry} = 0.103 \cdot 10^{0.517d}$ . The decrease in thermal conductivity was quite small above a wood content of 20% but the swelling due to water absorption continued to increase (a lot from 10%) [42]. Thus, limiting wood content to 20% was an interesting choice to reduce density and thermal conductivity, while avoiding excessive dimensional variations. The increase of porosity and consequently a lower density led to a decrease in thermal conductivity [41]. Thermal conductivities found in the references according to the dry density of the material are recapitulated in Figure 5. It can be seen that plant aggregates and fibers, by lightening the composites, led to a decrease in thermal conductivity. However, density is not the only parameter that influences thermal conductivity and a disparity of the conductivity values can be observed for the same density. The type of plant aggregate or fiber, the manufacturing technique or the testing machine can also play a role. Tortuosity has also been found to rise with the wood shaving content and a theoretical model has been created to correlate this physical characteristic with thermal conductivity [41]. Moreover, it was found that thermal conductivity decreased when particle length increased. A better volume occupancy was induced by the longer fibers [51]. The effect of fiber treatment on the thermal properties of fibered earth composites was also studied by Ledhem et al. [42]. Thermal conductivity was not modified by boiling water treatment but increased with linseed oil treatment. This rise was expected because of the higher thermal conductivity of oil in comparison with air and the higher density of the composite.

Thermal insulation decreased a lot when water content increased a little [9,43,56,57]. This can be explained by the fact that air in the pores was replaced by water, which is a better heat conductor than air [43]. Models have been proposed to link water and millet content to thermal conductivity [57] and to thermal capacity [56].

Thermal inertia is one of the principal advantages of earth material. Resistance to changes of temperature increases when thermal diffusivity decreases. The diffusivity was around  $4 \cdot 10^{-7}$  m<sup>2</sup>.s<sup>-1</sup> for earth material [39,43], whereas it was around  $12 \cdot 10^{-7}$  m<sup>2</sup>.s<sup>-1</sup> for concrete. However, thermal inertia was not improved by the addition of wood aggregates, and [43] showed that diffusivity was slightly higher with wood than without.



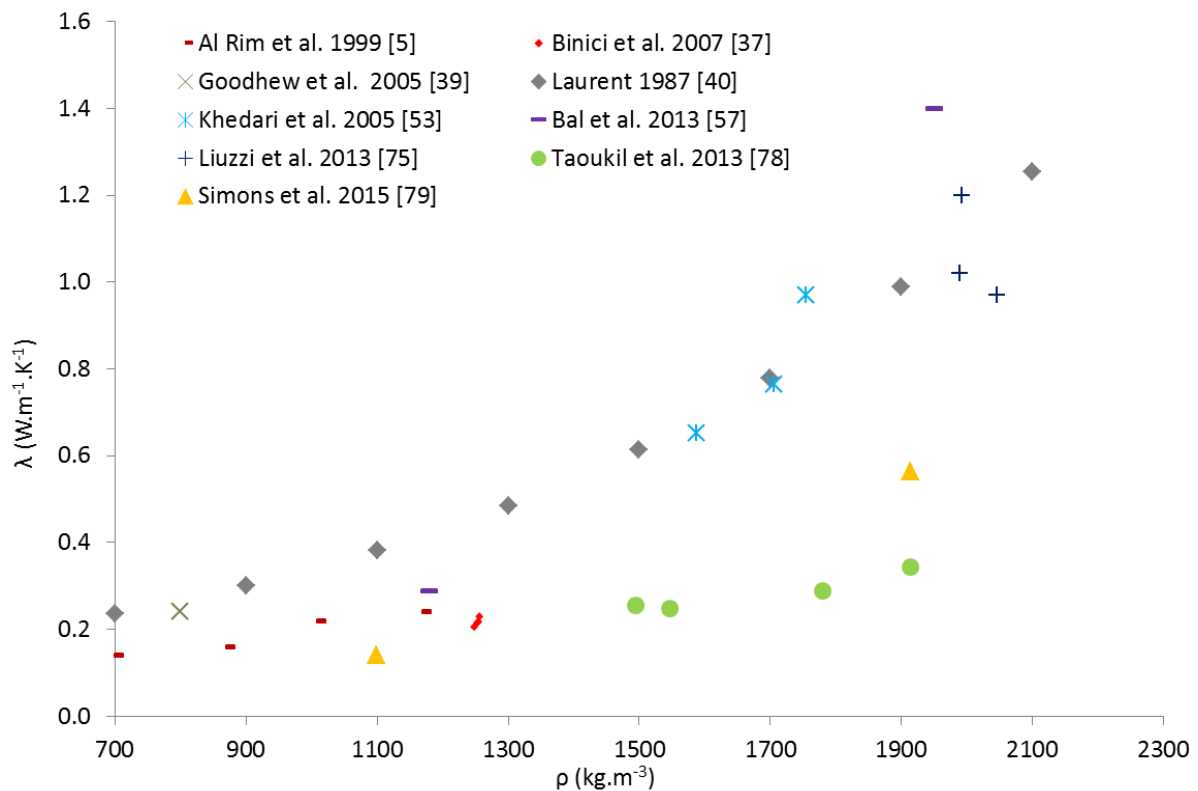


Figure 5: Thermal conductivity according to dry density from the literature

## 7. Durability of the composites

Vernacular heritage is very important all over the world and especially in France, where many villages are composed of earth constructions that were built more than 150 years ago [32]. Earth construction could therefore be considered as durable but, when it is not stabilized with a binder, earth can be very sensitive to environmental factors: meteorological and biological agents (microorganisms) and intrusion by organisms such as insects. Thus the durability of earth composites should be investigated. Few studies have focused on this topic but some authors [5,6,29,42,43] are conscious of the importance of performing such tests and verifications.

### 7.1 Resistance to water (rain)

Some tests were carried out in several studies but always in different ways. Durability norms created for conventional masonry cannot be applied to unfired earth. Hence, existing procedures had to be adapted. A test called “Bulletin 5 Spray” was adapted by [55]. A spray of water under pressure was applied for 1 hour at a distance of 50 cm from the sample and at pressures of 2.07 and 4.13 MPa. The depth of erosion was measured. The sample was considered to satisfy the water resistance criterion when the speed of erosion was less than 1 mm/min. A water dripping test called the “Geelong test” was performed on adobes in Achenza and Fenu [16]. The blocks were placed at an angle of 30° to the horizontal plane and received water for 30 minutes from a distance of 40 cm above the surface. The water dripping test proposed by [29] lasted 2 hours with the nozzle situated 18 cm from the sample surface and at a pressure of 1 bar. The water erosion test used [60] consisted in exposing a limited surface of a sample to a water jet at a pressure of 1.4 bar for 1 hour, again at 18 cm (Figure 6).



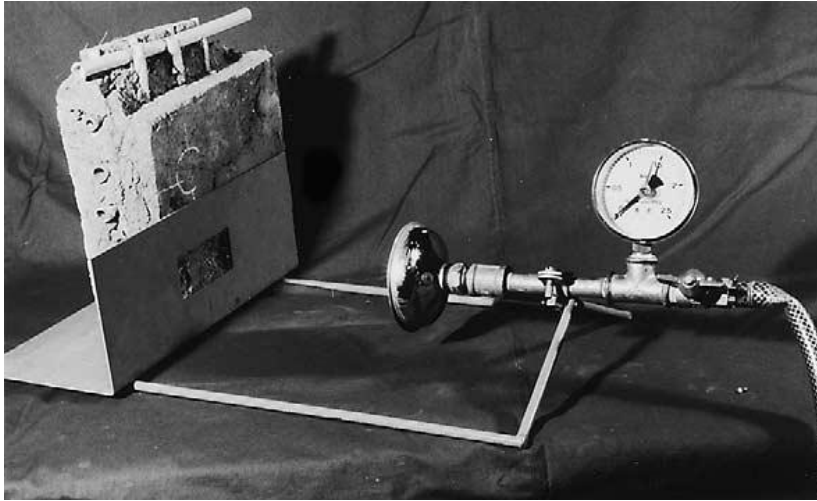


Figure 6: Erosion test equipment [60]

Earth containing natural polymer or cement was more resistant to water erosion than the other composites [16,29,60]. For example, samples composed of only earth were totally eroded in 13 minutes, but those containing cement or cactus pulp, resisted 1 hour of “raining” [60]. Only one study compared resistance according to the presence or absence of fibers [55]. All the samples satisfied the maximum criterion of 1 mm/min; soil-cement blocks had a negligible erosion rate whereas the soil-cement blocks with fibers had an erosion rate close to the limit. Using coir in that kind of blocks considerably decreased the durability against water. However, adding aggregates or fibers could be essential for block properties, thus more research is necessary to improve durability properties, by modifying the aggregate or fiber and cement proportions for example.

### **7.2 Resistance to wind-driven erosion and to abrasion**

Wind-driven erosion and abrasion, which are induced by friction, lead to a loss of mass of the material. This has to be limited to avoid recurrent maintenance. This property has been more studied for plasters (3 references) than for blocks (1 reference). Different methods have been tested to measure it: rubbing with an abrasive paper for 20 cycles [60], with different polyethylene brushes [30] or with a metallic brush [51]. Superficial cohesion was also measured with adhesive tape [30] by weighting it before and after testing. It was shown by Hamard et al. [47] that, the higher the clay content, the better the resistance to abrasion. Concerning aggregates or fibers, their presence did not influence resistance to abrasion for the plaster or for stabilizer, according to [60]. However, [51] showed that the abrasion coefficient decreased for hemp fiber contents between 0% and 0.4% by weight, then increase until the fiber content was 0.8%. Fiber length also had an influence: the coefficient was better for fiber lengths of 6 cm than 3 cm. Adhesion between fibers and matrix is better for longer fibers, which explains the better resistance to abrasion.

### **7.3 Freezing-thawing strength**

The ability of unfired earth and plant aggregates or fibers to resist freezing-thawing was studied by [49], but the material was considered as a soil and not as a building material. However, the results are presented here because they are interesting and applicable to earth building material. Only two articles have studied this property for earth blocks [80] and stabilized earth blocks [81], so much remains to be investigated.

Compression strength was measured before and after some freezing-thawing cycles. The higher the jute fiber weight content was, the better were the results (before or after cycles). The strength decreased with the number of cycles when the jute fiber content was between 0

and 0.50%. Beyond 0.50% of jute, the compressive strength increased, except for the third freeze-thaw cycle. The increase in strength was due to the tensile reinforcement brought by the fibers. Even if the soil was subjected to a compressive force, some strains were produced by tensile forces. [49]

#### 7.4 Biodegradation and microorganism development

All natural aggregates and fibers are biodegradable, as experience has shown, and are sensitive to biological attacks [50]. Over the centuries, organic material decomposes, e.g. ancient Roman adobe blocks have disappeared without trace [35] and only some prints persist of other old adobes [82]. This kind of degradation is often caused by microorganisms. Molds were observed on the sample by Flament [46] 10 days after its manufacture and fungi were observed on three earth mortars containing hemp fibers out of the four groups of binders in [83]. In this latter case, the biological growth decreased with the increase of binder and there was no proliferation at all with the hydrated air-lime mortars. Microbiological deterioration can also begin during storage [9] and it may be necessary to add a treatment before mixing the particles with the earth. Some small insects can live in earth based materials if they contain a lot of organic material such as straw or wood. However, it was the wattle and daub technique that presented the highest risk because there were more holes in it (not compacted) [1]. One example of insect degradation is given by [84] with *Centris Muralis* bees (Figure 7). By building their nests, these bees caused huge erosion similar to that caused by weather. It was shown that adobes with high fiber contents were less damaged than others.

To counter such biodegradation, some authors tested treatments (cf. subsection on aggregate and fiber treatment). The Bioterra project will study microorganism proliferation in addition to the mechanical and hygrothermal properties, which seem to be correlated. Sorption-desorption properties can have an impact on the durability of a composite material. A high relative humidity (above 70%) can encourage microbial activity inside the material and thus accelerate biodegradation of the plant material. The project should determine the species that can grow into the material and maybe limit their proliferation.

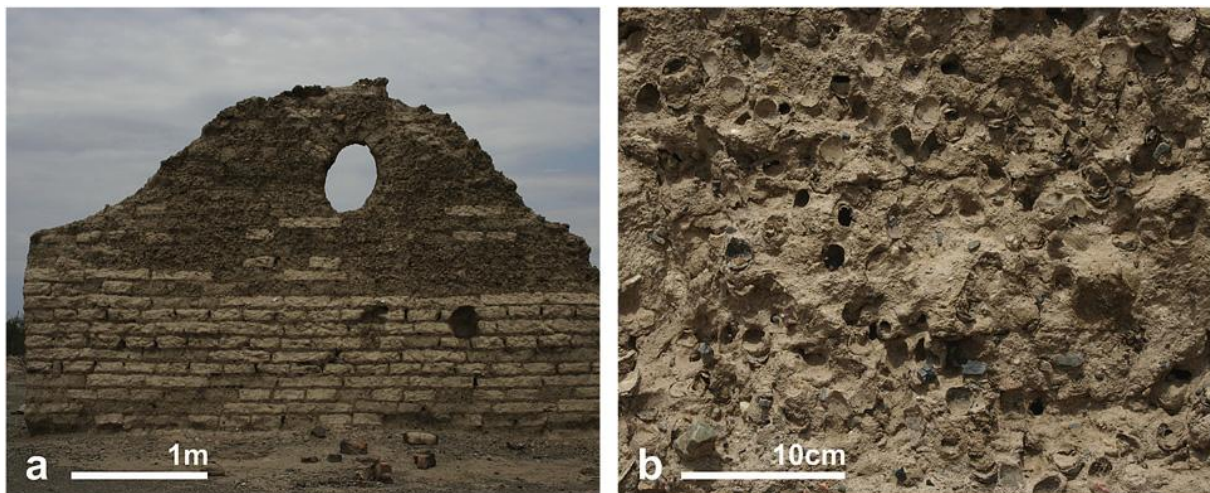


Figure 7: (a) Adobe wall damaged by biodeterioration. (b) Detail of superficially deteriorated area [84]

#### 8. Conclusion

Based on a review of plant aggregates and fibers incorporated into an earth matrix, the following conclusions can be drawn:

- The first concerns materials and plant aggregates or fibers. Various types of aggregates or fibers are used in various proportions, and have different shapes, chemical compositions,

capacities for water absorption and mechanical properties. Aggregate and fiber treatments are sometimes used to improve characteristics of the composites, e.g. by decreasing water absorption (dimensional variation), or increasing tensile strength (alkaline treatment and acetylation with some conditions), adhesion with the matrix and durability. Six different techniques have been studied, but CEB and stabilized blocks appear most frequently, mostly with cement.

- Concerning physical properties, a decrease of density is observed with the increase in aggregate or fiber content, as is a reduction of shrinkage cracks. Water absorption is increased with the addition of aggregates or fibers, because of their high capacity of absorption, but there have been very few studies. Sound insulation is better with the presence of plant aggregates or fibers, but this conclusion is based on a single existing study.
- Many studies have investigated mechanical properties. The effect of aggregate or fiber on compressive strength depends on the type of plant aggregate or fiber, the particle geometry, and the soil composition. It is generally improved with the addition of cement or another binder. Ductility is always improved with increased plant aggregate or fiber content, while Young's modulus is decreased. Tensile and flexural strengths depend on the shape of the plant particles: they are particularly improved when fibers are used.
- The water vapor permeability of soil is very high, but the influence of plant aggregates or fibers on this property has rarely been studied. A high capacity of the earth to balance air humidity can be noted, which seems to be increased by the addition of plant aggregates or fibers but, again, there are too few studies for a general conclusion to be drawn. Thermal conductivity decreases with the addition of plant aggregates or fibers and this is directly linked with the density of the material.
- Finally, few references deal with durability. Resistance to erosion and abrasion is not really influenced by the presence of plant particles or binder. The behavior of composite materials in compression after freezing-thawing cycles seems to be better with the addition of jute fiber, but only one study has investigated that topic. Concerning biodegradation, molds seem to be observed more often when plant aggregates or fibers are present, but it has been shown that fibers play a role of protection against bees. More work is needed on this vast topic.

Investigations are still needed to complete databases about earth composites with plant aggregates or fibers, especially concerning hygrothermal properties and durability. The main advantage of adding plant aggregates or fibers to earth materials is to improve their thermal insulation or, in other words, to save energy. Other properties of earth materials, such as their ductility or their capacity to balance air humidity, are often improved, whereas compressive strength can be decreased. An optimization of the plant aggregate or fiber content and shape is thus needed in order to obtain the most efficient material. Further experiments are still necessary, including on extruded blocks, which seem to be the easiest material to produce industrially.

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