Africa-Europe BioClimatic buildings for XXI century

REPORT ON MATERIALS AND CONSTRUCTION PRACTICES ADAPTED TO LOCAL CONDITIONS

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ABC 21 project

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Authors

Name	Email	Institution
Asmae Khaldoune	**a.khaldoune@aui.ma**	**AUI**
Othmane Noureddine	**o.noureddine@edu.umi.ac.ma**	**AUI**
Houssame Limami	**H.Limami@alumni.aui.ma**	**AUI**

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Executive summary

This report investigates the potential of different studied bioclimatic materials as construction materials in Europe and Africa. Earth and clay-based materials are assessed in terms of their mechanical, physicochemical and thermal performances. Earth as well as clay-based building materials reflected relatively low mechanical strengths, with a compressive strength in the range of 1 to 6 MPa, and improved thermal insulating properties less than 1 W/m.K. Earth and clay-based materials can be used in different building applications such as rammed earth constructions, earth bags, traditional and modern bricks etc

Stone material are also evaluated. Obtained findings confirmed that stone-based materials are characterized by their high mechanical resistance properties. Conducted experiments resulted in findings in the range of 25 - 100 MPa, 3 -10 MPa, and 3.15 -13 MPa for compressive, flexural and tensile strengths, respectively.

Plant based bioclimatic materials like straw, hempcrete and cork based building materials also reflect good physicochemical, thanks to their lightweight structure with a recorded density less than 0.95 g/cm3, making them good insulating materials with a great energy efficient potential reflected in a very low thermal conductivity in the 0.19-0.55 W/m.K range. Following the same trend line, on the one hand, wood and bamboo materials also reflected a strong mechanical threshold in terms of flexural, compressive and tensile strengths as well as bending threshold. Additionally, constructions with treated wood and bamboo materials show better mechanical and physicochemical properties compared to untreated ones, with gains in the 200-300% range. Finally, the report also goes through different types of fibrous vegetal and animal ecological materials, such as typha, wool and straw, with obtained findings reflecting their improved lightweight and insulating properties making them bioclimatic building materials with a great potential. A financial assessment is also conducted to evaluate which materials are the most cost efficient. The cost analysis reflects that shaped stone materials are the most expensive bioclimatic materials with an average cost of 280 euro/m² Africa and 550 euro/m² in Europe. While the most cost-efficient options is straw bale averaging at 70 euro/m².

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NOMENCLATURE

ρ: density in g/cm^3

W.A: Water Absorption in %

C.W.A: Capillary Water Absorption Coefficient CWA ($g/(cm^2.min^{0.5})$)

P: porosity in %

M.C: The moisture contents in %

A.S: Abrasive strength coefficient in g/cm^2

C.S: Compressive strength in MPa

F.S: Flexural strength in MPa

T.S: Tensile strength in MPa

M.O.R: Modulus of rupture in MPa

δ: elastic modulus in MPa

I.B: Internal bond strength in MPa

λ: Thermal conductivity in W/m.K

α: Thermal diffusivity in m^2/s

E: Thermal effusitivity in ($Ws^{0.5}/m^2K$)

Cp: Specific heat capacity in ($MJ/m^3.K$)

Rw: sound reduction index in dB

E.E: Embodied Energy is the energy required to extract, process and transport a material to the point of use or application in Mj/kg.

E.C: Embodied carbon (EC) is the amount of CO2 released to the environment, associated to the E.E, in Kg CO_2/t.

G.W: Global Warming Potential [kg Co_2/kg]

1. Introduction

Bioclimatic materials as well as the construction practice have important potentialities to offer to inhabitant. Their evaluation needs to be carried out with a detailed perspective. With this purpose, best practices for the application of bioclimatic design and case studies of use of local materials should be selected from the existing literature, analysed and capitalized.

This report exposes a review of:

- Earth-based materials and techniques, including adobe, bricks with additives, rammed earth and earth-bag constructions.
- Cork-based blocks, Hempcrete and Typha based blocks as eco-friendly building elements;
- Stone construction since it is one of the most abundant and used materials to reach natural comfort;
- Straw bale construction with existing building styles;
- Sheep wool as ecological insulation material;
- Properties of Wood and Bamboo;
- Cost assessment of construction of materials selected;
- Some codes and regulations utilized in the field.

2. Earth-based constructions

Europe and Africa have a long history of Earth construction and therefore an accumulated experience of thousands of years. However, a noticeable switch to concrete based constructions can be observed in overall the word, this is leading to a loss of expertise in the field, loss of local jobs, increase of greenhouse gases and CO2 emission and decrease of the energy efficiency of the buildings.

Earth constructions are Variety of construction techniques uses earth as basic material. The properties of all earth techniques are practically similar. In this section, Adobe, Mud-bricks, Rammed earth and Earth-bags construction are the covered ones.

2.1 Adobe

The most popular building material in the world was earth bricks before the explosion of concrete and steel construction recently. The return to earth construction techniques in general is necessary to overcome the current various environmental challenges. In their simplest form, basic mud bricks are made by mixing earth with water, placing the mixture into moulds, and drying the bricks in the open air. Additives are included to enhance some specific properties which make the material adapted to local environment. Section 2.2 covers a literature review of clay bricks with natural additives. When a high pressure is applied during the manufacturing of bricks, they are called Compressed Earth Bricks/Blocks (CEB). The addition of a chemical binder makes them stabilized [1].

Their embodied energy is the lowest of all building materials but the use of chemical additives such as cement, excessive transport and the use of firing process can increase the actual embodied energy of all earth construction [2].

The adobe does not reach mechanical strength as high as concrete or fired brick. However, it is enough for a specific type of one to two-story building. Some studies observed that the adobe is strong enough, ductile and resistant against earthquakes [3]. The most common values of compressive strength being between 0.8 and 3.5 MPa. The bulk density is about 1.87 g/cm3 [4]. Concerning the thermal properties, earth could store heat absorbed during the day, keeping the interior relatively cool, because of its high specific heat capacity. When the outside temperature drops at night, the energy stored during the day in the walls would be emitted inside the building. Which makes earth efficient to reach thermal comfort.

The construction technique consists on joining the bricks mortar and to build walls, vaults and domes. In West Africa, the Nubian vault is a construction that is restarting to penetrate some countries where it is possible to construct these buildings in vaults without risk. This ancient architectural method uses earth bricks as elementary material, consisting on a self-supporting arched form. By help of the Nubian Vault, building does not require the use of increasingly rare timber beams or expensive and inconvenient imported metal roofing sheets. Originating in upper Egypt, it uses only adobe made from local earth and mortar. It is classified as durable, comfortable, ecologically sustainable, affordable, and vernacular [5]. The Association Voûte Nubienne “AVN” has simplified and codified the vault building technique developed in Egypt [6].

The Nubian vault technique of AVN is described briefly following the steps below [6], [7]:

1. **Preparation of elements of construction**: including: building site, orientation, materials and equipment. The soil is examined and the right formulation is obtained by adding the right proportions of sand and swilling clays other additives like straw might be also added.
2. **Foundations:** the deep is ranging from 30 to 80 cm depending on the wall type and geological properties of the chosen location. They are filled with rocks, bound with an ordinary earth mortar
3. **Walls and Openings:** Load-bearing walls, Gable walls, doors, windows, cupboards, alcoves, and shelving (Figure 2-1). In a load-bearing wall, each course is made up of a row of bricks laid lengthwise alongside a row laid width wise, using an earth mortar. The orientation of the bricks alternates with each course. While, a gable walls are built in courses of bricks simply laid lengthwise.

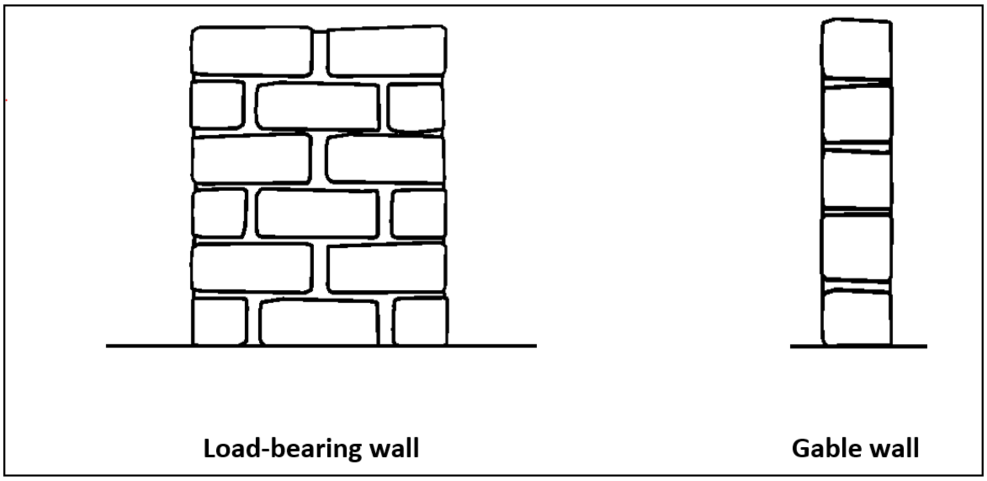

Figure 2-1: Types of walls for Nubian Vault technique.

4. **Constructing arches and the vault:** The bricks are laid at a 60-degree angle, so the first brick is placed on the gable wall, and successive bricks are placed on the front bricks. The central axis of the vault is defined by a guiding cable, which is utilized to ensure a constant radius during construction. The best form isn't always an excellent semicircle. However, as a substitute barely elliptical on the top, as this form is towards the perfect catenary curve wherein all forces are in compression and the ensuing vault is as sturdy as it is able to be (Figure 2-2).
5. **Roof construction:** the roof is water-proofed, using plastic sheeting locally produced, then covered with a rendering.
6. **Interior of NV:** The internal walls are smooth and a nest plastering is conducted using finer clay particles and lime.

Figure 2-2: Construction of the vault. Source: AVN.

2.2 Clay bricks with additives

Clay bricks are considered one of the most popular construction materials thanks to their good physico-mechanical and mechanical properties [8]. However, according to some research conducted in cold and rigid weather climate conditions during cold seasons, clay constructions do not provide the thermal comfort to accommodate standard living conditions as [9]. One of the suggested approaches to solve this issue is using environmentally friendly and ecological additives materials to produce clay-based materials with enhanced physicochemical, mechanical and thermal performances.

This part of the report goes through major research findings available in the literature review tackling the performances of unfired and earth bricks with ecological construction material additives.

2.2.1 Compressed earth blocks (CEB) samples with banana fibre additive.

Table 2-1: Properties of compressed earth blocks (CEB) samples with banana fibre additive.

Additive proportion (%)	C.S	F.S	M.O.R
0%	3.98	0.56	0.56
1%	6.02	0.83	0.83
2%	6.58	0.99	0.99
3%	6.47	1.02	1.02
4%	6.39	0.94	0.94
5%	6.13	0.86	0.87

Mostafa et al. [10] evaluated the mechanical behaviour compressed earth blocks (CEB) with banana as ecological fibre additives. Earth-additive mixtures of (0%, 1%, 3%, 4% and 5%) reflected a respective compressive strength of 3.98 MPa, 6.02 MPa, 6.58 MPa, 6.47 MPa, 6.39 MPa, and 6.13 MPa; a flexural strength of 0.56 MPa, 0.83 MPa, 0.99 MPa, 1.02 MPa, 0.94 MPa, and 0.86 MPa; and a modulus of rupture in the range of 0.56 MPa, 0.83 MPa, 0.99 MPa, 1.02 MPa, 0.94 MPa, and 0.87 MPa. Incorporation of fibrous additives improved the brick's mechanical performances. This was attributed to the creation of isotropic matrix between the structures composed of soil fibrous additive matrix network. This created a stability as fibres appeared to distribute tension throughout the bulk of material.

2.2.2 Unfired clay brick samples with seaweed biopolymer additive.

Table 2-2: Properties of unfired clay brick samples with seaweed biopolymer additive.

Additive proportion (%)	C.S	F.S	A.S
0%	0.5	0.25	9.7
0.1%	0.75	0.35	19.5
0.25%	1.45	0.75	25.5
0.5%	1.65	1.25	45.3

Dove et al. [11] assessed the performance of unfired clay bricks with seaweed biopolymer additives. Low additive content in the range of (0%, 0.1%, 0.25% and 0.5%) were used to produce unfired clay brick samples. The mechanical properties of produced specimens were investigated in the form of compressive strength, flexural strength and abrasive strength coefficient to evaluate the mechanical resistance performance of the studies samples. Obtained findings reflected improved mechanical properties of sample bricks with higher additive content, with an increasing: compressive strength from 0.5 MPa to 1.65 MPa; flexural strength from 0.25 MPa to 1.25 MPa; and abrasive strength coefficient from 9.7 g/cm^2 to 45.3 g/cm^2. The improved mechanical properties were explained by a higher viscosity, high molecular weight alginate providing longer polymer chains and prompting a more crosslinking site per chain, improving the clay-additive bonding. Produced samples can serve as on-loadbearing applications such as infill within timber frames.

2.2.3 Unfired clay brick samples with Typha-fibre additive.

Table 2-3: Properties of unfired clay brick samples with Typha-fibre additive.

Additive proportion (%)	P	ρ	C.W.A	C.S
0%	1.14	1.79	25.93	6.16
1%	3.02	1.75	29.17	5.95

Additive proportion (%)	P	ρ	C.W.A	C.S
3%	4.25	1.69	33.15	5.32
7%	9.05	1.61	41.25	4.86
15%	12.11	1.54	52.95	4.05
20%	14.95	1.51	58.75	3.67

Limami et al. [12] investigated the effect of Typha-fibres additives to unfired clay bricks. Various clay-additive proportions have been prepared (0%, 1%, 3%, 7%, 15% and 20%). Higher additive content produced more porous brick samples with higher porosity percentages from 1.14% for reference samples up to 14.95% for 20% brick samples. Bulk density analysis was also used to evaluate the lightweight properties of produced samples. Obtained results were in the range of 1.79 g/cm^3 for reference samples and 1.51 g/cm^3 for 20% additive percentage. An increasing trend was observed for capillary water absorption coefficient findings from 25.93 g/(cm^2.min$^{0.5}$) reference samples to 58.75 g/(cm^2.min$^{0.5}$) for 20% based brick samples. While measured compressive strength decreased from 6.16 MPa for reference samples to 5.95 MPa, 5.32 MPa, 4.86 MPa, 4.05 MPa, to 3.67 MPa with 20% additive proportion. The obtained results were explained by the production of high porosity brick samples with higher additive percentages. This is due to the interlayer spacing created inside the bricks' matrix due to the formation of Typha fibres-clay flocculants. This resulted in the production of lightweight bricks with decreasing compressive strength and increasing water absorption coefficient.

2.2.4 Compacted earth bricks with Alfa fibers' additive.

Table 2-4: Properties of compacted earth bricks with Alfa fibers' additive.

Additive proportion (%)	C.S	F.S	C.W.A	ρ	λ
0%	19.27	4.07	36.45	3.01	1.51
1%	18.90	3.80	48.29	2.24	1.36
1.5%	15.64	2.44	60.59	2.18	1.27

Ajouguim et al. [13] discussed the behaviour of compacted earth bricks with Alfa fibers' addition. A couple of additive proportions were used for this purpose, in the range of (0%, 1% and 1.5%). Compressive and flexural strengths reflected decreased values with additive incorporation respectively, from 19.27 MPa and 4.07 MPa for reference samples, to 15.64 MPa and 2.44 MPa for 1.5% additive content. Higher additive content also produced brick samples with a more lightweight structure and higher water absorption rates. In fact, capillary water absorption and density measurements reflected a respective 36.45 g/(cm^2.min$^{0.5}$) and 3.01 g/cm^3 to 60.59 g/(cm^2.min$^{0.5}$) and 2.18 g/cm^3 for 1.5% brick based samples. Thermal performance of produced samples was evaluated via thermal conductivity measurements. A

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1.51 W/m.K recorded thermal conductivity was observed for reference samples compared to a 1.27 W/m.K one for 1.5% samples, representing a 16% gain in thermal conductivity with the use of Alfa fibres additives. The properties of the bio-composite were influenced by the percentage of fibres content. The increase of Alfa decreased the mechanical properties and diminished the thermal conductivity of the specimens. This was attributed the augmentation of hydrophilic fibres character and to the segregation fibre phenomena resulting from fibre overloading. These two factors amplify the porosity that occurs during the drying period of the specimens.

2.2.5 Raw earth bricks with date palm waste additive.

Table 2-5: Properties of Raw earth bricks with date palm waste additive.

Additive percentage (%)	C.S	M.O.R	F.S	λ	C_p
0%	6.83	233.5	2.26	0.677	0.650
2%	2.92	118.05	1.50	0.587	0.680
4%	1.29	64.18	0.69	0.501	0.660
6%	0.83	39.73	0.56	0.443	0.560
8%	0.70	34.58	0.40	0.389	0.520

Khoudja et al. [14] evaluated the mechanical and thermal effect of date palm waste additives on raw earth brick materials. An in-depth mechanical analysis was conducted by testing the specimens' compressive and flexural strengths as well as their modulus of rupture. The incorporation of 10% additive content reflected reductions of 91% and 87%, respectively, for compressive and flexural strength, from 6.83 MPa and 2.26 MPa for reference samples to 0.55 MPa and 0.29 MPa for 10% samples. The brick samples' thermal performance was assessed following thermal conductivity and heat capacity measurements, with recorded thermal gains in the 49% range. In fact, thermal conductivity reached 0.342 W/K.m with the incorporation of 10% additive content, compared to 0.677 W/m.K for reference samples. While heat capacity parameter recorded 0.44 compared to 0.65 of reference samples. It can be observed that obtained findings recorded a bad effect of date palm waste additive on the flexural and compressive mechanical performance. While thermal insulating properties recorded great energy gains.

2.2.6 Earth bricks with barley bio-aggregates additive.

Table 2-6: Properties of earth bricks with barley bio-aggregates additive.

Additive Percentage (%)	C.S	ρ	λ
0%	4.8	2.017	0.471

Additive Percentage (%)	C.S	ρ	λ
3%	3.3	1.519	0.254
6%	3.8	1.315	0.155

Giroudon et al. [8] assessed earth bricks with barley as a bio-aggregate additive in terms of their compressive strength, bulk density and thermal conductivity for a various proportions (0%, 3% and 6%). An overall decrease in compressive strength was observed from 4.8 MPa of reference samples to 3.8 MPa with the incorporation of 6% additive. Bulk density recorded a gradual decrease from 2.017 g/cm^3 for reference samples, to 1.519 g/cm^3 for 3% additives, to 1.315 g/cm^3 for 6% additive samples. While thermal conductivity recorded great improvement with a decrease from 0.417 W/m.K for reference samples to 0.254 W/m.K with the 3% incorporation, to 0.155 W/m.K for 6%. These findings highlight the importance of considering several ways of recycling agricultural by-products in building materials.

2.2.7 Unfired earth bricks with corn cob additive.

Table 2-7: Properties of unfired earth bricks with corn cob additive.

Additive Percentage (%)	C.S	ρ	λ	C_p
0%	4	1.891	0.57	0.774
3%	3.2	1.671	0.35	0.790
6%	1.8	1.565	0.26	0.808

Laborel-Préneron et al. [9] discussed the behaviour of unfired earth bricks with corn cob additive for 0%, 3% and 6% content. On the one hand, compressive strength recorded a decrease from 4 MPa for reference samples to 1.8 MPa with the additive of 6% corn cob proportion. While bulk density parameter also decreased from 1.891 g/cm3 for reference samples to 1.565 1.891 g/cm^3 with 6% additives. On the other hand, thermal insulation properties recorded great gains in the 55% and 5% range for thermal conductivity and heat capacity, respectively. In a nutshell, the incorporation of decreased additive content resulted in a significant drop in mechanical strength which would require an increase in the wall thickness to maintain a sufficient load-bearing capacity. In addition, obtained findings showed an increase in specific heat capacity and a decrease in thermal conductivity for studied specimens, reflecting great improvements in the specimens' thermal insulating properties.

2.2.8 Unfired earth bricks with wood aggregates' additives.

Table 2-8: Properties of unfired earth bricks with wood aggregates' additives.

Additive percentage (%)	C.S	ρ	C.W.A
0%	7.25	1.62	1.45
1.5%	6.5	1.61	1.25
3%	5.15	1.60	0.90

Masuka et al. [15] evaluated the effect of wood aggregates on unfired bricks' mechanical and physicochemical performances. Mechanical compressive strength recorded a gradual decrease from 7.25 MPa for reference samples to 6.5 MPa for 1.5% additive, to 5.15 MPa for 3% additive content. Bulk density parameter also recorded a decrease with higher additive content from 1.62 g/cm3 for reference samples, to 1.61 g/cm^3 for 1.5% additive proportion, to 1.60 g/cm^3 for 3% additive samples. Following the same behaviour, capillary water absorption also recorded in the range of 37% with the addition of 3% additive compared to reference samples. This study developed and evaluated the mechanical strength and water resistance properties of improved low-cost unfired earth bricks stabilized by wood aggregate additives. Unfired earth bricks reinforced by wood aggregates had dry compressive strength significantly higher than unfired earth bricks of control samples. While reductions in bulk density and capillary water absorption were also observed, resulting in the production of unfired earth bricks with lightweight structure.

2.2.9 Unfired earth bricks reinforced by agricultural wastes.

Table 2-9: Properties of unfired earth bricks reinforced by agricultural wastes.

Additive percentage (%)	ρ	λ
0%	1.70	0.96
1%	1.59	0.59
3%	1.45	0.31

Ashour et al. [16] assessed the effect of agricultural waste additives on unfired clay bricks' bulk density and thermal conductivity performances. On the one hand, a decrease in the bulk density parameter was observed from 1.70 g/cm^3 for reference samples, to 1.59 g/cm^3 for 1% additive proportion, to 1.45 g/cm^3 for 3% additive samples. Thermal insulating properties reflected an improvement with higher additive proportions as thermal conductivity noted a decrease from 0.96 W/m.K for reference samples to 0.59 W/m.K with the 1% incorporation, to 0.31 W/m.K for 3%, reflecting an overall 68% gain in thermal insulating properties.

2.2.10 Earth bricks reinforced by date palm fibres.

Table 2-10: Properties of Earth bricks reinforced by date palm fibres.

Additive Percentage (%)	C.S	λ
0%	4.5	0.656

1%	4.47	0.565
2%	4.1	0.550
3%	2.2	0.487

Hakkoum et al. [17] investigated the behaviour of earth bricks reinforced by date palm fibres in terms of their mechanical and thermal performances for (0%, 1%, 2% and 3%) additive proportions. Mechanical compressive strength recorded a gradual decrease from 4.5 MPa for reference samples to 2.2 MPa with the incorporation of 3% additive content. Following the same behaviour, thermal conductivity noted a decrease from 0.656 W/m.K to 0.487 W/m.K for 3% based additives, recording a 26% thermal gain at the expense of 51% reductions in mechanical resistance of prepared specimens. This decrease in the thermal conductivity and compressive strength as a function of the increase in the percentage of the fibres in the mixture due to the presence of fibres creating voids after the oven drying process, and total carbonization giving rise to pores, resulting in a product having a porous structure and cell, improving insulation, decreasing conductivity and increasing thermal resistance. Therefore, the incorporation of palm fibres or any other combustible plant will be favorable for the improvement of thermal performance and reductions in compressive strength properties.

2.2.11 Unfired bricks with cork additives.

Table 2-11: Properties of unfired bricks with cork additives.

Clay-Additive formula	ρ	λ
Clay	1.77	0.51
mc (0.7 cm) + c-co (1.4 cm) + mc (0.7 cm)	1.22	0.29
mc (0.7 cm) + c-co (1.2 cm) + mc (0.7 cm)	1.28	0.32
mc (0.7 cm) + c-co (1.07 cm) + mc (0.7 cm)	1.47	0.35

El Wardi et al. [18] evaluated the density and thermal conductivity parameters of unfired bricks with additives in a sandwich formula binder via cement. A thicker cork additive layer decreased the density and thermal conductivity of the specimens, reflecting lighter sandwich material with improved thermal performances. In fact, a 31% gain in lightness was achieved with the 1.4 cm thick cork layer compared to reference clay material; and a 44% gain in thermal insulating properties. This was attributed to thicker cork layer providing more pore structures in the sandwich material, and producing lighter materials with good thermal performances as a result.

2.2.12 Process of fabrication of clay bricks.

Unfired clay bricks are made of earth materials with generally some additives and are left to air dry to make them stronger and well bonded with mortar and potentially finished using different polishing techniques. Unfired clay bricks' manufacturing come in two types: traditional or modern bricks.

- **Traditional bricks:**

Traditional clay units such as cob and mudbricks are bricks made manually without using any advanced technique. This method has been used for centuries to produce bricks with diverse dimensions depending on the application. These structures all share the property of having thick walls usually above 300 mm to cover the loss of bond strength due to mortar. Nevertheless, it is important to note that the standard wall thickness for internal partitions of sun-dried earth units is around 100 mm [19].

Figure 2-3: Traditional brick-making process [20].

- **Modern bricks:**

Modern sun-dried clay units are manufactured with precise tolerances with the help of extrusions or pressing systems to improve their properties, and hence their quality. In addition, the manufacturing process of modern bricks is the same as the one for fired clay bricks, with the exemption of high-firing temperatures providing high potential energy gains [19].

Figure 2-4: Modern bricks manufacturing process [21].

Manufactured modern or traditional bricks come in different shapes and forms depending on the field of application. Generally, these bricks can be either solid full or hollow material structures [22].

Table 2-12: Solid/Full bricks vs Hollow bricks.

	Solid/Full bricks	Hollow bricks
Raw material	Made by a mixture of clay, sand, lime or/and additives	Made up of natural clay amalgamated with other natural additives
Uses	Wall structures, paving footpaths, sidewalks, driveways, etc.	Load and non-load-bearing structures, internal and external walls for high-rise buildings, partition walls etc..
Properties	• Cost efficient (raw material availability) • Strength and durability • Low maintenance cost • Can be recycled • Easy to manufacture	• Better insulating properties • Energy savers • Good fire resistant • Lightweight structures (60% lighter)
Standard size	• 190x90x90 mm • 190x90x40 mm	• 200x150x200 mm • 400x400x400 mm
Dry density	Between 1.7-1.92 g/cm^3	Between 0.69-0.78 g/cm^3
Compressive strength	Between 7.5-10 MPa	Around 3.5 MPa
Water absorption	Should not be more than 20 % of its weight	Around 15% of its weight.
Thermal conductivity	Between 0.6-1 W/m.K	Between 0.28-0.31 W/mK

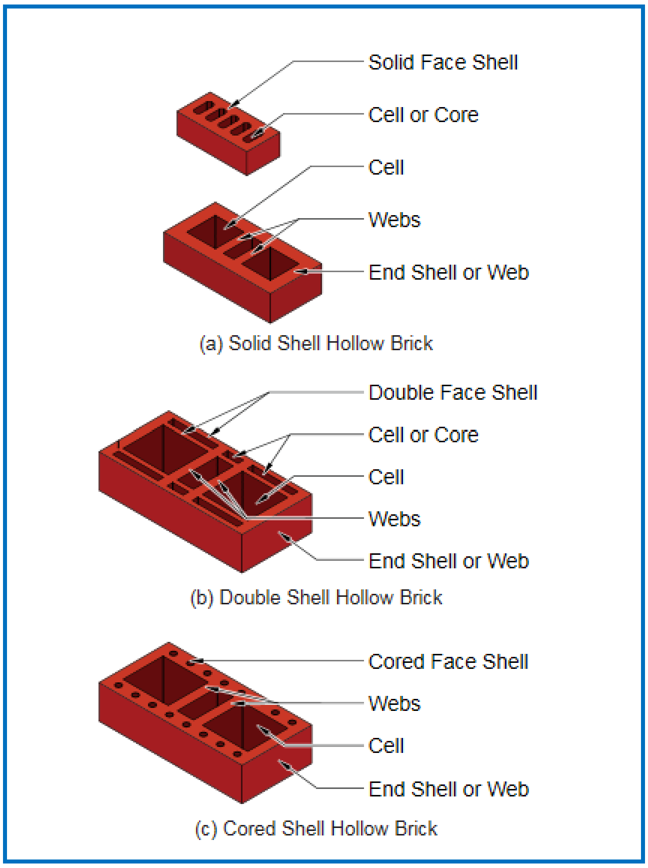

Figure 2-5: Illustration of hollow bricks [23].

2.3 Rammed earth

The rammed earth construction technique is an ancient method that is based on using natural raw materials such as earth to build especially walls. This technique is classified as sustainable building method which makes it, nowadays, subject of interest. It uses local materials, which makes producing low embodied energy and eco-friendly because the materials are naturally producing little wastes. Wonderful heritage is still lasting all over the Europe (chateaux and rural houses) and Africa (Entire villages in North Africa) [24]. The main advantages of rammed earth construction are [25]:

- Low cost for materials
- Requires minimal water
- Unsophisticated method of construction
- Produces buildings aesthetically attractive
- Suitable for building load-bearing
- Long lasting
- Fire resistance
- Environmentally friendly

In the other hand, the main disadvantages may be summarized in the intensive labour required, the poor insulation properties and the unsuitability for vaults and domes.

2.3.1 Unstabilized rammed earth properties

Table 2-13 shows the key properties of unstabilized rammed earth.

Table 2-13: Mechanical, thermal and physical properties of unstabilized rammed earth.

References	Experimental findings / Properties discussed		Comments
[26]	**Composition**	5% – 40% clay 15% – 40% silt 25% – 70% sand and fine gravel 25% – 46% liquid limits	Range of values indicated in literature
[27]	**ρ**	1.79 – 2.19	—
	M.C	7% – 21%	—
	C.S	0.81 – 2.46	Almost all the studies have applied the load in the perpendicular direction of the earth layers.
	δ	34 – 1050	
	λ	0.6 – 1.6	The values found in literature with a normal density are generally between 1.0 and 1.4 W/mK
	R_w	57 [dB] for a wall 50cm thick	

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References	Experimental findings / Properties discussed		Comments
		Ranges of 58 dB for a wall 30 cm thick	Densities are between 1.9 g/cm^3 and 2.1 g/cm^3.
	G.W	0.004	unstabilized rammed earth generates lower emissions than any other building material or technique.

Studies show an enormous dispersion in the Elastic modulus which may generate problems during the application of seismic loads. This is due to the sample methodology of manufacturing, including sample size and shape, compaction, density, moisture content and also due to the testing procedure adopted. The wide range of combinations between these parameters makes it difficult to assess clear relationship between them and the mechanical properties.

The insulation properties of rammed earth as well as other earthen techniques are not much interesting: ranging generally between 1.0 and 1.4 W/mK for thermal conductivity and 57 [dB] to 58 [dB] for the sound reduction index. Similar characteristics are offered by traditional ceramic brick. For this reason, the walls are built with excessive thicknesses.

2.3.2 Construction practice

Traditional construction uses wooden poles, the earth mixture is rammed manually between temporary formwork panels and compressed. Modern technology replaces the pole with a mechanical ram. The formworks are removed immediately after completing the wall. The detailed construction process is presented below [28]:

Figure 2-6: Rammed earth walls of Meknes - Morocco.

- **Analyzing the soil:** the suitability of the local soil for construction as well as the optimum formulation needs to be examined, for this, a range of tests are carried out to determine. If the native soil is inadequate for building, it can be blended with or replaced by soil from another source.
- **Preparing the site:** this operation consists on cleaning the site, stake out the outline of the building, the soil then is excavated to a depth that guarantees a level surface.

- **Laying the foundation:** the concrete strip foundation is the most common for the establishment of foundation, which is very similar to that for low-rise buildings. Footing size is determined by the type of supported structure as well as the soil bearing capability underneath the foundation.
- **Framing the walls:** traditionally, wood forms were used. After the mold was filled with fully compacted soil, framework would be removed and reset to form the next section of wall. More efficient methods now allow forms to be constructed for the entire section of the wall.
- **Tamping the soil:** 10-15 cm layer of moistened soil is placed inside the form, and a worker drops the tamper made of a heavy wooden block from a height of 30-46 cm. Pneumatic tampers are now employed facilitating the majority of work. A layer was considered to be properly rammed when the noise made by the impacting tamper changes from a dull thud to a ringing sound after many repetitions over the entire surface of the layer. At this point, the soil has been compacted to about half of its original volume. Another layer then is added, and the tamping process is repeated. The forms are removed after the tamping is completed.
- **Finishing the walls:** Rammed earth walls may not be plastered. Instead, the surface is wiped with a moist towel immediately after removing the formwork. Interior faces of walls are often finished with plaster.

2.4 Earth-bags construction

Earthbag constructions, also known as earth filled in, is a construction method where dry soil is poured into long synthetic tubes stacked upon each other to form building structure [29]. Table 2-14 summarizes the materials' properties of earthbag construction for different building structures.

Table 2-14: Properties of earthbag construction.

System	Material	Thickness (m)	λ	ρ	Cp
Roof [30]	Earthbag	0.28	2.18	2.19	1
Walls [31]	Earthbag	0.35	2.18	2.19	1
	Earthbag (buttress)	0.70	2.18	2.19	1
	Exterior lime mortar coating	0.04	1	1.70	1

Table 2-15 provides a step-by-step guide to earthbag construction [32].

Table 2-15: Method of construction following the earthbag technique.

Step	Description
Tools and materials preparation	Woven polypropylene bags and earth and cement construction materials

Filling the bags	Filling 90% of the bags capacities to leave enough space to sew the bags closed and ensuring the same size to keep walls level.
Sew/stitch the bags from the top	Fold the bags from the top and use a wire to sew them closed.
Gravel bags and add barbed wire	Align earthbags against each other and attach them with a barbed wire to avoid spillage.
Place additional courses with sheetmetal slider	Use a sheetmetal slider to place additional courses so bags do not snag on the barbed wire
Repeat	Repeat the same process using earthbags until the opted level is reached
Tamping	Tamp earthbags after each course is complete.

3. Cork-based bricks

Table 3-1: Properties of unfired building material of granular cork composite with slag cement.

Cement/Cork ratio	ρ	C.S	F.S	λ
100% cement, 0% cork	1.5	6.75	7.25	0.37
50% cement, 50% cork	0.77	2.65	4.45	0.29
25% cement, 75% cork	0.61	1.72	2.64	0.19

Merabti et al. [33] assessed the thermo-mechanical and physical properties of granular cork composite with slag cement. Obtained results reflected that higher cork content produced lightweight building materials with lower mechanical resistance properties, reflected in the decrease in measured compressive and flexural strengths. While thermal conductivity noted a decrease with higher cork content, reflecting the specimens improved thermal insulation properties in the 48%-22% range.

4. Hempcrete

Hempcrete or hemp-lime is a new developed material, rapidly expanding across Europe, made from a mixture of hemp hurds with lime and water and is more lightweight than regular concrete. Depending on the mix variables, hempcrete can be used as roof, wall and slab insulation. Compared to manufactured insulating products or ordinary blocks, hempcrete performance details are difficult to generalize due to the range in formulations and additives. The industrialization of the manufacturing process is getting more and more interest at the international scale. One of its main advantages is that it is considered to be carbon negative thanks to the high amount of hemp in the mixture which allows carbonation during the use phase of the blocks and photosynthesis during plant growth [34]. Table 4-1 presents the main properties of hempcrete.

Table 4-1: Summary analysis of hempcrete properties [35], [36]

ρ	δ	C.S	λ
0.291 – 0.920	5 – 140	0.18 – 4	0.179 – 0.542

Large variations in densities are available because the mass of the product depends highly on the mass composition of composite. This affects directly the other properties such as mechanical and thermal behaviour. The thermal conductivity is very low which offers a good insulation. Hemp concrete is considered to be a green building material not only because of its low embodied carbon but also because of its ability to regulate heat, moisture, and relative humidity [35].

Hempcrete blocks are used to construct non-load-bearing structures infill walls, since it does not have the required strength to support forces as shown in the table. As blocks, it can be easily installed, generally by applying mortar. Wood stud framing is most common making it suitable for low-rise construction. It may also be used as insulation panels for walling and roofing.

The manufacturing process as reviewed by Jami et al. [35] is explained below:

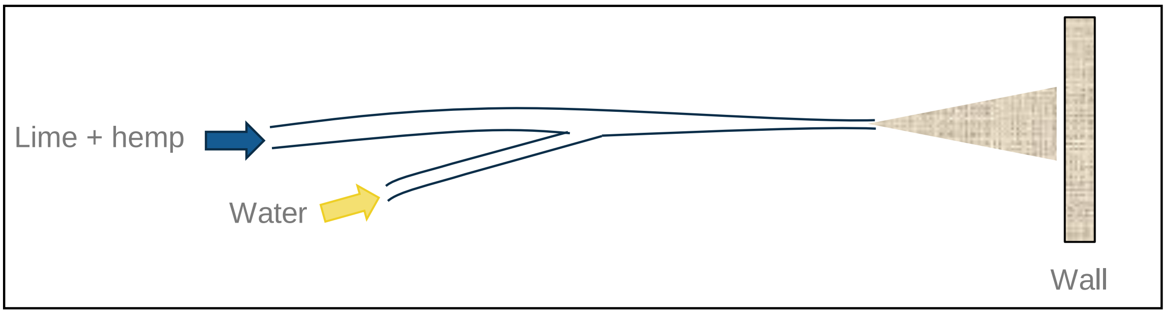

Figure 4-1: Projection process of hempcrete.

After providing the materials, hemp stalks are shredded to shaves of 40±5 mm. Lime hemp concrete (LHC) walls can be made on site proceeding with two methods: either by pouring or by projection. The first consists on tamping manually the mix into a temporary formwork. For the projection process (Figure 4-1), the dry mixture controlled by the operator is fed into the lance through a pressurized air stream and mixed with the water at the nozzle before the entire mix is projected onto the target site. Blocks of hempcrete may be prepared to by casting in moulds following an industrial process.

5. Stone

Stone structures-built hundreds of years ago are still used today which make stone as durable as a building material. It does not require any manufacturing process, and it does not need to maintain, it emits no airborne pollutants. It is also an attractive material that will outlive today's buildings, and it can be salvaged from one building to be reused or repurposed in another. Stone can be used as thermal mass for space heating and cooling. Some stones also have good solar reflectance [37].

Figure 5-1: House built with stones in Ifrane – Morocco.

On the Earth's crust, there are a number of rocks produced by various processes. The rocks are classified into three categories which are: Igneous (or magmatic) rocks, Sedimentary rocks and Metamorphic rocks [38]. The table 5-1 shows the most common used stones in architecture of each category [39].

Table 5-1: Most common used stones in architecture.

Igneous	Sedimentary	Metamorphic
Granite, Basalt	Limestone, Sandstone	Slate, Marble

Igneous rocks are the primary rocks that originally formed when the molten magmatic material cools under natural process and subsequently hardens. The rocks may form either underground or above the Earth's surface when volcanic lava flows [40].

The sedimentary rocks are formed by following a process of precipitation, deposition, cementation and solidification on the Earth surface. Small and large particles are eroded by wind, water, or other natural agents, transported, accumulated and then compacted [41].

The metamorphic are formed by metamorphism of pre-existing igneous, sedimentary, and metamorphic rocks with changes in crystal form in solid state, at temperatures ranging from 1150 to 200 degrees Celsius and pressures exceeding 1500 bars [42].

The following paragraph discusses and analyses essential properties of stones which are directly related to architecture and construction, listed in the table above.

5.1 Properties analysis

Table 5-2: Summary analysis of stone properties.

Ref	Comments	Experimental findings / Properties discussed				
[43]	Discusses characteristics for each type of stone used as a building material. It also reviews several		Sandstone	Limestone	Granite	Slate
		ρ	2 – 2.35	1.95 – 2.55	2.6 – 2.65	2.7 – 3.1

Ref	Comments	Experimental findings / Properties discussed				
	works, done in the UK, on stone performance related to ecological construction. And finally, it proposes some interesting construction configurations.	**W.A**	3 – 20	3 – 15	0.1 – 0.4	0.05 – 0.4
		P	10 – 35	5 – 30	0.2 – 1	0.15 – 1
		C.S	25 – 100	25 – 60	175 – 300	225 – 400
		F.S	3 – 10	2 – 12	10 – 30	50 – 90
		EC	0.062	0.098	0.075	0.096

Ref	Comments		Sandstone	Limestone	Granite	Basalt	Marble	Slate
[44]	Offers huge amount of detailed information. Properties shown, are collected from several scientific papers from different regions, and presented in this book. **Values on side are summarized and given as intervals of minimum and maximum.**	**ρ**	2.03 – 2.53	1.63 – 2.70	2.62 – 2.67	2.68 – 2.71	2.65 – 2.7	2.79 – 2.81
		W.A	0.04 – 10.6	_	0.05 – 21.9	0.05 – 0.38	0.01 – 0.38	0.01 – 0.57
		P	6.29 – 35	0.52 – 34.59	0.11 – 1.03	_	0.14 – 0.60	0.13
		λ	0.65 – 1.69	0.76 – 2.04	1.34 – 3.69	0.51–2.03	1.59 – 4.00	_
		C.S	49 – 85	25 – 165	130 – 180	115 – 200	75 – 135	90 – 220
		F.S	4.5 – 9.5	5 – 17	11.5 – 16.5	10 – 25	12 – 18	25 – 83.2
		T.S	3.5 – 13	5 - 12	12.5 – 17	_	8 – 17	22 – 42

Stone as a building material has high-density, low water absorption, high-thermal capacity but low thermal resistivity: It is generally a poor insulator unless used in extensive thicknesses, as has historically been adopted.

The porosity differs enormously for sedimentary stones (up to 35%) compared to magmatic and metamorphic stones. This latter is due to the process of forming where the deposition and cementation of particles are not done perfectly, and leave behind a considerable number of pores. Same for mechanical properties, magmatic and metamorphic rocks are stronger because of the high porosity presented in sedimentary stones.

It was, also concluded that natural stone exhibits a low environmental footprint when compared with other typical building materials (less than 100 KgCO2/t of EC).

The identification of mechanical parameters of masonry structures which is complex. In fact, strengths and stiffness of masonries depend on many factors, such as strengths of component blocks and mortar, blocks shape, volumetric ratio between components, and wall texture.

A fair assessment can be made only by in situ test [45] on the basis of a qualitative criteria evaluation, as proposed in [46]. The method, the Masonry Quality Index (MQI), consists of the evaluation of the presence, the partial presence, or the absence of certain parameters that define the “rule of the art,” namely a set of construction techniques that, if executed during the construction of a wall, provide a good mechanical behaviour and ensure the compactness and monolithic nature of the structure. A synthetic evaluation of the wall quality is obtained through three overall scores, the MQIs, that define the quality of masonry in relation to three actions: vertical actions, out-of-plane actions, and in-plane actions. An estimation of the mechanical parameters (compressive strength, shear strength, and Young's modulus) of masonry can be obtained through correlation curves, obtained from experimental data.

5.2 Obtainment process

The first phase to obtain stone for construction is the process of collecting stones from exposed surface of natural rocks which is quarrying. Extracting stones can be carried out either by hand tools, Machines quarrying or Blasting. A primary cut is carried out to open a bench, generally having a volume variable between 2 m3 and 15 m3. The second phase is the cutting where, machineries cut stone blocks at dimensions and thicknesses variable according to the market requests. When necessary, a previous squaring of the block is carried out. Finally, with the finishing phase, stone products can be submitted to different surface treatments according to the customer requests (such as smoothing, polishing, sand blasting, etc.) [47].

5.3 Construction practices and methods of application

Natural stone is suitable for working to diverse applications. The most typical ones holding market share across stone industry include [43]: Aggregates, Cladding/façade masonry, Conservation of existing structures, Flooring, Garden landscaping, Internal fixtures, Kerbing and paving, Roofing, Structural masonry. Typical building stone applications are indicated in Figure 5-2.

Masonry buildings when subjected to vertical loads, they demonstrate good mechanical behaviour and typically have excellent resistance to sustain or accidental loads. In the case of horizontal actions, such as those induced by the earthquakes, masonry structures exhibit an intrinsic weakness due to the low tensile strength of the material. This phenomenon is called a box behaviour [48].

For walls masonry, depending on the shape of the stone elements and their assembly, different methods of construction can be distinguished [48]:

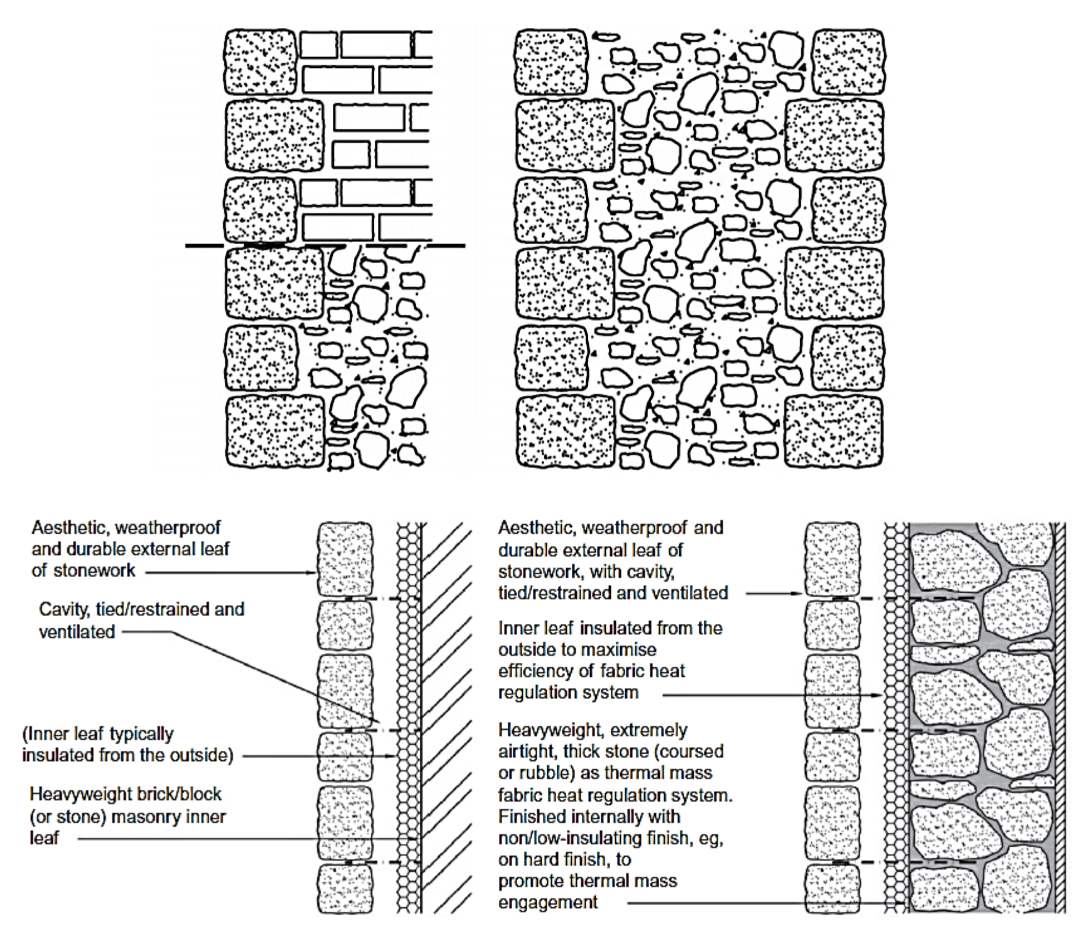

Figure 5-2: Typical construction configurations of stone masonry in modern and traditional structural contexts [43].

- Dry stone walls: blocks of stones that are laid down without any mortar to bind them together. The structural integrity of dry-stone walls arises from compression forces and the interlocking of the stones (Figure 5-3-A).
- Rubble masonry: blocks of undressed or rough stones placed with mortar (Figure 5-3-B).
- Ashlar masonry: regularly shaped stone blocks, with a dressed exposed face, which may feature a variety of treatments: tooled, smoothly polished, or rendered with another material for decorative effect (Figure 5-3-C).
- Masonry with wood reinforcing: very common in seismic-prone areas. The tensile strength of wood offers reinforcement against horizontal loads and enables the dissipation of substantial amounts of energy in the case of earthquakes. Two main categories of wood reinforcement can be identified: the hooping and frame systems. This system can be found in seismic regions of the Mediterranean from the Balkans to Turkey, Maghreb, Greece, and Italy (Figure).
- Stone is reinforced with concrete: walls are made by two stone exterior layers used as formwork for the subsequent casting of reinforced concrete (Figure).

- Gabion walls: This technique consists of cages - generally made of galvanized steel wire or mesh-filled with rocks without mortar (Figure 5-3-D).

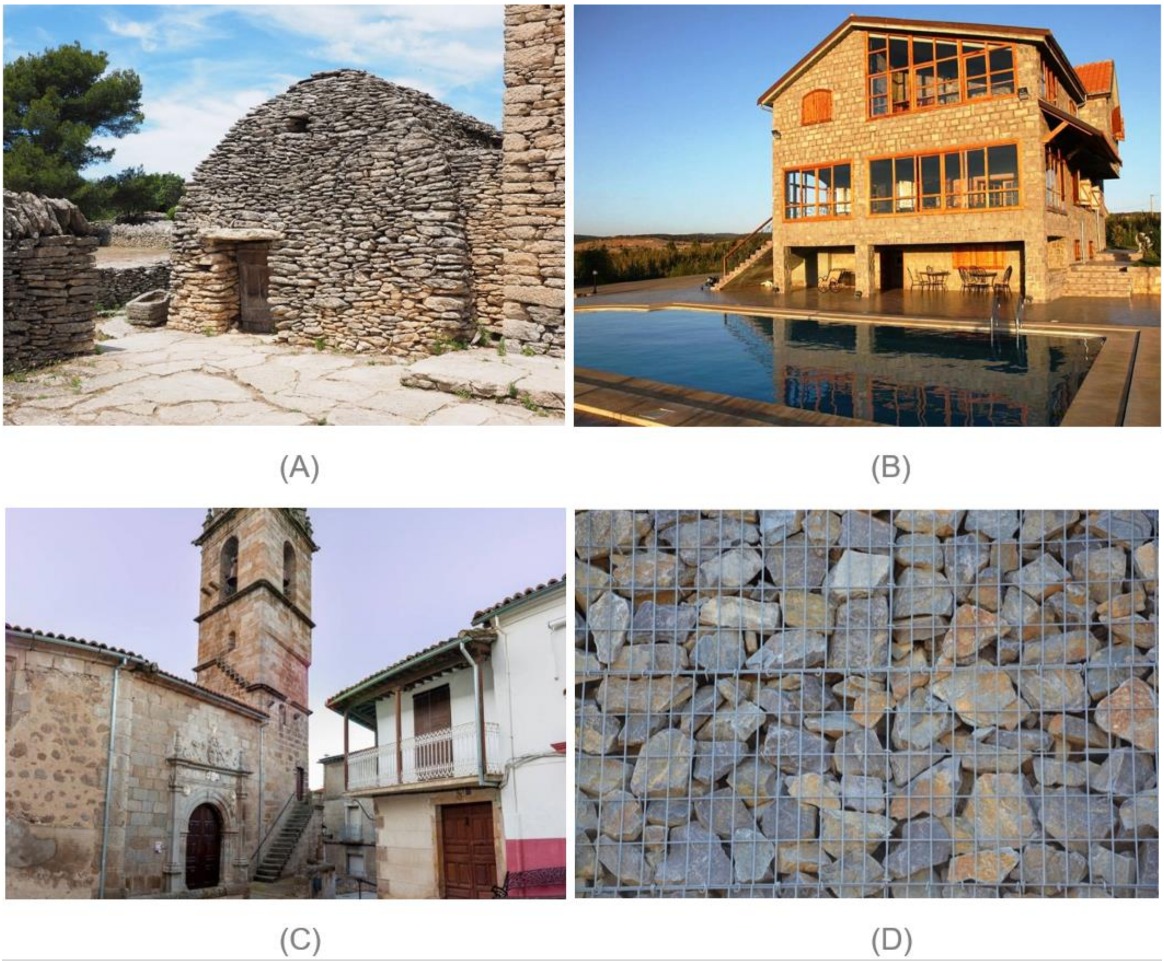

Figure 5-3: Examples of stone construction practices: (A) Dry stone construction - Village des Bories (open-air museum in France) / (B) Rubble masonry - Ifrane (Morocco) / (C) Ashlar masonry - Church of Santa Maria de la Asuncion of Banos de Montemayor, Extremadura, Spain / (D) Gabion wall.

6. Straw

6.1 Straw-bale construction

6.1.1 Properties analysis of straw-bale construction

Historical uses of straw include thatching roofs, linings for internal plasters and reinforcement for traditional earthen building techniques, including adobe and cob [49]. A new construction technique using straw has been developed during the 19th century in Nebraska, individual bales are laid in courses to form walls of buildings without a binder, then coated [50].

There are three significant advantages in using the straw-bale construction [51]:

- Straw-bale buildings have significantly lower embodied energy and embodied carbon than conventional materials, which makes its impact less environmentally.

- Straw-bale walls can provide high-quality physical properties including sound insulation, seismic stability of structure.
- Because of the relatively high thermal insulation properties of straw-bale walls, straw bale houses have low heating energy load and cooling energy load.

Figure 6-1: Rome's First Straw Bale House, Italy. By Herbert Gruber, source: http://esbg2015.eu/romes-first-straw-bale-house-italy/

Straw is the remaining stalk of cereal plants, in particular, wheat, maize, rice, barley, oats, rye and sorghum, after grain has been harvested [52]. Straw can be baled into a variety of standard sizes, with the most common size used in construction being the two-string bale that measures approximately 1000 mm × 450 mm × 350 mm [49].

An understanding of materials and straw-bale construction technologies requires an analysis of the properties of straw bales, including structural, thermal, hygroscopic, acoustic properties, resistance to fire and a life cycle assessment (Table 6-1).

Table 6-1: Summary analysis of straw bales properties.

References	Experimental findings / Properties discussed		Comments
[49], [51]	ρ	From 0.06 to 0.18 In load-bearing construction, following the compaction, the density should be higher than 130 kg/m3	Depending on the type of application
[49], [53], [54]	δ	A highly variable elastic modulus ranging between 0.05 and 0.9	Non-linear behaviour. Orthotropic visco-inelastic behaviour. Depending on the orientation of straw bale.
[55], [56]	λ	From 0.03 to 0.194	Depending on temperature, packing density, moisture content and orientations of the fibres.
[55]	α	From 0.1 ×10^{-6} to 3.6 ×10^{-6}	

References	Experimental findings / Properties discussed		Comments
[49], [57]	**R_w**	From 42 to 55	
[49], [58]	**M.C**	The moisture content of straw bales has been found being in the range of 10% to 12% at 23 °C and 80% humidity	Straw is a hygroscopic material, which means that it will adsorb water vapour from the air and absorb liquid water when exposed to a suitable source.

Straw-bale as a building material presents interesting properties. The density is a key factor that contributes in the determination of all other parameters. Straw bales can be used as a primary structural elements to provide vertical load support or as in-fill element with frame construction may be used instead to ensure the building strength [59]. More details of construction practices are provided in next section. A load-bearing application requires a density not less than 130 kg/m^3, but as a second application, no restrictions are dictated.

As mentioned in the table, unplastered straw-bale walls exhibit an orthotropic, visco-inelastic behaviour with an elastic modulus ranging between 0.05 and 0.9 N/mm^2. Correlations models are proposed, Maraldi et al. [54] suggest that $E = a.\ \rho^2$ between Young's modulus E and density ρ, with "a" a coefficient that depends on the orientation (laid flat bales on edge) and type of straw (wheat; hard wheat; rice; oat; barley; corn; sorghum; and millet).

Thermal performances of straw bales are the most important advantage in their use. By having a good combination of temperature, packing density, moisture content and orientations of the fibres, thermal conductivity can reach 0.03 [W/mK] as mentioned, which is a very exploitable as an insulator.

Moving to acoustic property, common straw bale walls are not good enough to be sound insulating structures. Even if walls are commonly 50 cm thick, the low density of bales limits their efficiency, especially at low frequencies. A 50 [dB] sound reduction index can reduce only the noise of a small quiet town, or sounds in the kitchen.

During construction, fire is a huge risk that needs to be managed. Though, a structure of compacted straw bales walls shows high resistance to flame spread and temperature increase, since oxygen, the combustive agent, is mostly removed during compression [57].

Studies have been carried out to evaluate the environmental impact of straw-bale construction compared to different insulation materials and construction techniques. It has been proven that straw bales have the least environmental impact compared to other insulation materials (mineral wool, cellulose fibre, polystyrene, etc.) [60]. In comparison with a bricks wall, Gonzáles has estimated that the energy embedded in straw-bale or straw-clay blocks to be about 28 MJ and 40 MJ per 1 m^2 respectively, hugely less than the same area covered by fired bricks (488 MJ/m^2) or concrete blocks (169 MJ/m^2) [61]. Besides, straw-bale construction is considered carbon negative as a material and has the potential to offset the carbon footprint of the building [49].

6.1.2 Construction practices and methods of application

Two typical techniques of construction are mostly common:

Post and Beam style (Figures 6-2 and 6-3)

A framing style, uses a structural framework to hold roof loads, and the straw bales are either wrapped outside the framework or in filled between the framing members [62] (Figures). Therefore, prefabrication off site may be enabled, which leads to a panelised construction methodology and architecture [49].

This method offers three main advantages: (1) less need to worry about the straw bales wetting, (2) lower quantity of loose straw on the ground of the building site, which means lower fire risks during construction, (3) use of metal or wood for the frame, which are approved as structural materials by building codes [57].

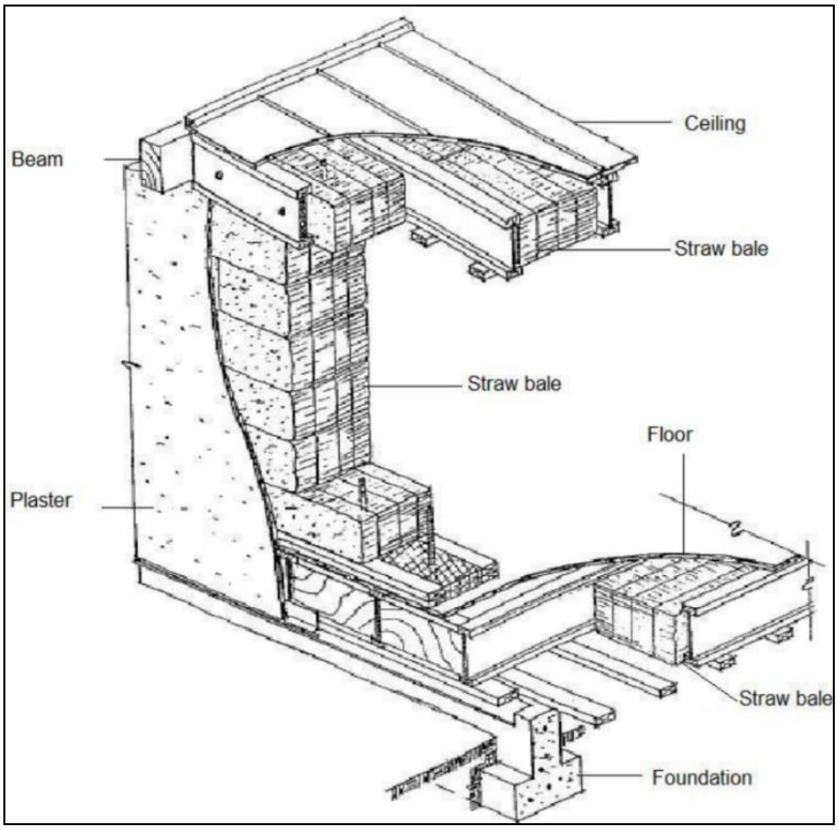

Figure 6-2: Cross-section for in-fill wall system [62].

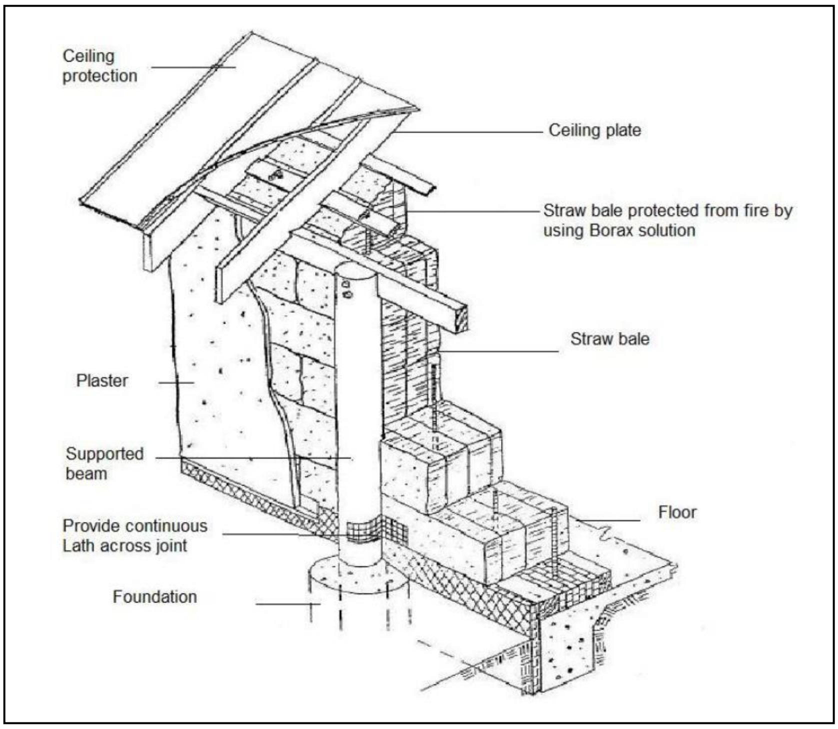

Figure 6-3: In-fill straw bale wall section with supports outside the wall [62].

Load-bearing style (Figure 6-4)

Called also Nebraska style, Load-bearing construction consists on using the straw bale themselves as the structural elements. Thus, they are in charge of sustaining the roof (Figure).

“Bales are laid horizontally to form a wall measuring around 500 mm wide once plastered. Timber stakes, such as hazel or in some cases broom handles, are used to secure the base of the wall to the footing and pin the bales together. Once the bales have been stacked to storey height (around seven or eight courses high), the wall plate is placed on top, and then the wall is compressed (prestressed), typically using external strapping wrapped around the wall, such as fencing wire or packaging tape, which greatly improves the robustness of the wall. Thereafter, the internal plaster and external render coats of between 20- and 80-mm thick when complete are applied directly onto the straw in two or three coats” [49].

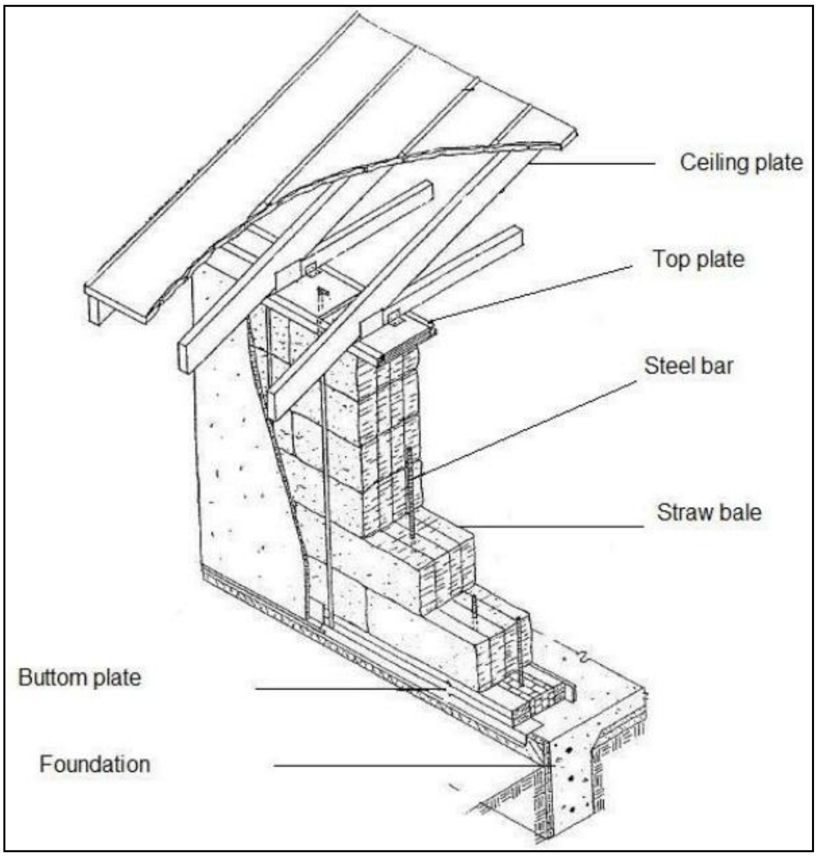

Figure 6-4: Load-bearing wall cross section [62].

6.2 Thatched roof

Thatching is a style of roof building using dry vegetation, which is laid into layers and bundles, constructing a beautiful and warming roof [63]. This technique is very affordable and commonly available in the EU. The three main thatching materials in use today are water reed, long straw and combed wheat reed (straw). Sedge, a grass-like plant which grows in wetland areas, is also used extensively in ridging [64]. Water reed requires a complete roof strip back to timber when it is renewed, whereas combed wheat straw (reed) and long straw can be partially stripped and re-thatched [65]. In some other regions in the world, palm is used to as a thatching material.

Figure 6-5: Dogon village of Ireli in Mali. Photo credit: Shutterstock

Before the material can be used for thatching, it needs to be made into yealms. A yealm can be described as a tight, compact layer of straw, which has been 'tidied' and is level at both ends. Yealming is a lengthy procedure which takes place on the ground and is basically carried out in order to straighten the straw and prepare it into manageable amounts for use on the roof. When re-thatching with long straw, it is not usually necessary for all of the old material be removed from a roof. The thatcher will normally only remove existing material back to a base coat and the new straw is then fix to this with hazel spars.

7. Typha-based Bricks

Typha is an interesting building material that is widely used in Africa, several researches are conducted on Typha based bricks. Dieye et al. [66] assessed the behaviour of Typha australis as a building material with clay as a binding agent. The results are presented in Table 7-1. We can see that building blocks with lower Typha content produced lighter building structures with high density and porosity levels. An increase in mechanical properties in the form of compressive and tensile strengths was also observed with higher Typha proportions. Finally, small reductions in thermal properties, illustrated in thermal conductivity and effusivity were also observed with an increase of Typha material. Increasing additive percentage has inversely proportional relation with mechanical properties and a directly proportional one with thermal properties. This is due to high water content and moisture in bricks with high additive content, as clay matrix reduces the fibres porosity.

Table 7-1: Properties of unfired building material of crushed Typha australis fibres.

Typha Percentage (%)	ρ	P	C.S	T.S	λ	E
84.90%	1	46.7	0.31	0.29	0.127	0.242
84.22%	1.11	40	0.49	0.43	0.136	0.259
81.48%	1.17	36.3	0.68	0.52	0.142	0.268
78.11%	1.23	23.3	0.91	0.78	0.158	0.295
77.13%	1.30	21.9	0.97	0.79	0.163	0.315

Bajwa et al. [67] evaluated a composite building material of Typhacattail and wheat straw in terms of their waster absorption of threshold of rupture properties. Obtained findings reflected higher water absorptions for higher cattail content. A decrease in mechanical threshold was also noticed when increasing the proportion of Typha cattail in the composite material. This was attributed to loose packing distribution density of the composite materials creating pore structures in the formed material's interlayer structures.

Table 7-2: Properties of unfired building material of Typha cattail and wheat straw.

Additive Percentage (%)	W.A	M.O.R	I.B
25% Cattail: 75% Wheat Straw	20%	226	0.11
50% Cattail: 50% Wheat Straw	21%	228	0.02
75% Cattail: 25% Wheat Straw	22%	448	0.12
0% Cattail: 100% Wheat Straw	23%	150	0.02
100% Cattail: 0% Wheat Straw	32%	73	0.07

8. Wool

Sheep wool is considered the insulation material that emits less greenhouse gases. Literature describes sheep wool as a sustainable material. The production of wool fibres concerning release of carbon dioxide is estimated around 1.7 kg CO^2 to 36.2 kg CO^2 /kg fibres [68].

Sheep wool is an excellent insulation material. Not just that, but it is also a non-toxic insulation material. It can be merited for being environmentally friendly, health conscious, renewable, and absorbs pollutants in the atmosphere such as Sulphur dioxide and nitrogen dioxide through a process known as chemisorption. Additionally, sheep wool is naturally fire resistant without any flame retardants. In terms of moisture, sheep wool can absorb up to 35% of water during humid weather, then ejecting it back into the indoor environment during dry times without damaging its insulating ability [69]. Another benefit of sheep wool is high sound absorption coefficient compared to glass wool and polystyrene foam, which offers sheep wool the ability to reduce noise.

Table 8-1: Sheep Wool Properties [70], [71].

λ	R-value (100 mm) [m2K/W]	E.E [Mj/kg]	Index of Reduction of Impact Noise [dB]	Rw [500-2000 Hz]
0.034-0.054	0.034-0.054	12.6	18	0.38-0.77 (thickness of 60 cm)

8.1 Obtainment process

The first step in obtaining sheep wool is shearing the sheep; then, sorting it based on colour. White wool usually costs more than grey or black wool since it is possible to dye it with different colours. The second step of the process is washing bundles of wool with warm water to clean from dirt, grease and vegetable matter. The next step is drying the wool; then scour it in order to have all the fibres flowing in the same direction. After obtaining a highly thin layer of insulation, it is then sent to a conveyor belt and to a pendulum. The pendulum moves back and forth to generate multiple wool layers. Those layers are bonded using a mechanically driven needle punch that joins them together. [72] To make sheep wool unappealing to bugs and moths, it is recommended to treat raw sheep wool with borate, lime, or food grade diatomaceous earth.

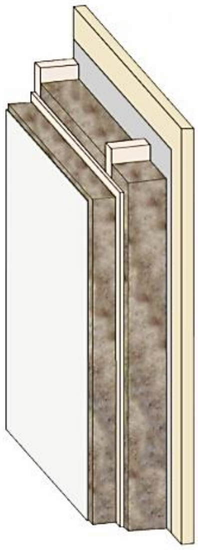

Figure 8-1: Wall insulated with sheep wool. Source: Lana Term Insulation

8.2 Comparison of sheep wool with fiberglass

The production of glass fibres triggers serious environmental consequences as compared to producing natural fibres. Glass production and glass fibre production both depend primarily on fossil fuels. In terms of demand for non-renewable energy, glass fibre production consumes 5 to 10 times more as compared to natural fibre. Hence, GHG emissions from glass fibre are higher than those of natural fibre. Regarding the construction industry, wool fibres are mainly used for thermal and acoustic insulation. Joshi et al. demonstrated that glass-fibre-reinforced composites undergo an inferior life cycle assessment to natural-fibre-based composites due to high environmental impact and lower transportation efficiency [73]. Another major benefit of sheep wool compared to fiberglass is its ease of installation as an insulating material, while installing fiberglass requires the person wearing preventive equipment to avoid inhaling certain fibres that would cause respiratory issues in the long run.

Table 8-2: Life Cycle Assessment (LCA) of Different Insulation Materials [74]–[78].

Insulation Material	λ	G.W	E.E	E.C

Rock wool	0.033 - 0.040	1.511	16.8 - 22.12	1.05
Cellulose Fibre	0.035 - 0.04	1.831	0.94 - 4.24	_
Wood wool	0.065 - 0.07	0.124	20	0.98
Mineral wool	0.036 - 0.045	1.2	16.6	1.2
Fiberglass	0.032 - 0.040	2.1	28 - 34.60	1.35
Sheep wool	0.034 - 0.054	- 0.3	12.6	_

Several life cycle assessments of insulation materials have been assessed, which are summed up (Table 8-2). Sheep wool is undoubtedly the adequate insulation material in terms of thermal conductivity, global warming potential since it has a negative GWP, and primary energy is lower compared to fiberglass or the other insulation materials.

9. Wood

Timber is considered a widely used bioclimatic and structural construction material. About 122 million m3 of wood was produced in Europe in 2016, reflecting its prominent potential [79]. In addition, wood is characterized with its high strength and stiffness as well as being a good cost-efficient construction material alternative. Wood based materials' mechanical properties vary due to their various growth and natural conditions and origins [80].

This part of the report will discuss major research findings available in the literature review tackling the performances of wood as a construction material and its suitability.

Table 9-1 illustrates the different mechanical properties, in terms of modulus of elasticity, bending strength and stiffness, and failure load, of different types of dowel laminated timber and wood constructions as discussed in the literature review.

Table 9-1: Mechanical properties of laminated wood and timber constructions.

Reference	Species	Application	Modulus of Elasticity (GPa)	Bending Strength (MPa)	Test Method
[81]	UK larch	Dowel laminated beam (single row)	10	34	Four-point bending
[82]			**Bending stiffness [kN/mm]**	**Failure load [kN]**	
	Sugar maple	Welded dowel laminated beam	0.37 ± 0.04	1.70 ± 0.14	Three-point bending
		Glued-laminated beam	1.52 ± 0.05	5.75 ± 0.76	
	Yellow birch	Welded dowel laminated beam	0.34 ± 0.01	1.79 ± 0.04	

	Glued-laminated beam	0.98 ± 0.04	5.21 ± 0.52	Glued-laminated beam	
[83]	Maritime pine	Glued-laminated beam	3	14.9	Three-point bending
[84]	Spruce	Nailed laminated beam (double row)	0.04	3.20	Four-point bending
	Beech	Bonded dowel laminated beam (single row)	0.06	3.21	
	Beech	Welded dowel laminated beam (single row)	0.08	3.25	
[85]	Irish Spruce	Unfastened beam with no dowels/adhesive (i.e. stacked lamellas)	0.18	21	Four-point bending
		Beech	Dowel laminated beam (20 dowels)	0.4	
		Beech	Dowel laminated beam (32 dowels)	0.465	
		Beech	Dowel laminated beam (44 dowels)	0.565	

Wood construction materials can also be used in a densified form, after compression. Multiple studies investigated the effect of densification and compression of wood, at different compression ratios, on the materials' mechanical and physicochemical properties, as presented in Table 9-2. A notable increase in the compression ratio resulted in an increase in density and mechanical properties. In fact, 70% compression ratio samples reflected the highest mechanical properties with a longitudinal modulus increase in the 300% range.

Table 9-2: Mechanical and physicochemical properties of different wood structure species.

Reference	Species	Compression ratio (%)	Density	Young's modulus (MPa)	Shear modulus (MPA)
[86]	Japanese cedar	0	0.322	753	31
		33	0.403	338	122
		50	0.564	354	170

		67	0.886	523	256
		70	1.162	3111	878
[87]	Japanese cedar	**Compression ratio (%)**	**Density**	**Flexural modulus (GPA)**	**Flexural strength (MPA)**
		0	0.3	11	86
		70	1	30	245
[88]	Balsam fir	**Compression ratio (%)**	**Young Modulus (MPA)**	**Shear Modulus (MPA)**	
		0	830	38	
		60	284	21	
[89]	Sitka spruce	**Compression ratio (%)**	**Density**	**Flexural modulus (GPA)**	**Flexural strength (MPA)**
		0	0.458	14	90
		33	0.606	25	120
		50	0.7	26	108
		60	0.817	30	96
		67	0.8	31	115
[90]	Pieca sitchensis	**Compression ratio (%)**	**Density**	**Compressive strength (MPA)**	
		0	0.46	2.6	
		80	1.30	87.6	

Song et al. (2018) [90] also investigated the effect of compression different wood construction species. Obtained findings confirmed the increase of mechanical threshold of wood structures after compression by almost 300% to 400%, as presented in Table 9-3.

Table 9-3: Compressed vs uncompressed mechanical strength of different wood structures.

Species	Longitudinal tensile strength (MPa)	
	Compressed	Uncompressed
Oak (Quercus)	115.3	584.3
Poplar (Populus)	55.6	431.5
Western red cedar (Thuja plicata)	46.5	550.1
Eastern white pine (Pinus strobus)	70.2	536.9
Basswood (Tilia)	52.0	587.0

F. Peron et al. (2020) [91] investigated the thermal properties of different wood structures and species using the transient plane source method in both dry and wet conditions. Table 9-4 presents the physicochemical, in terms of dry density and porosity, of different wood structure species, as well as their thermal conductivity parameter.

Table 9-4: Thermal and physicochemical properties of different wood structures.

Species	Dry Density	Porosity	Thermal conductivity
Oak	0.757	49	0.16
Fir	0.341	77	0.09
Larch	0.505	66	0.10
Elm	0.597	60	0.16
Ash	0.608	59	0.18

The same study, conducted by F. Peron et al. (2020) [91], also assessed the effect of water content, at different proportions, on the measured thermal conductivity on the analysed wood structure species, as shown in Table 9-5.

Table 9-5: Effect of water content on thermal conductivity of different wood structures.

Species	Water content (%)	Thermal conductivity
Oak	0%	0.31
	2%	0.33
	4%	0.34
	7%	0.35
Ash	0%	0.24
	2%	0.25
	7%	0.26
	11%	0.27
Elm	0%	0.22
	5%	0.24
	7%	0.25
	10%	0.26
Fir	0%	0.15
	4%	0.16
	7%	0.17
	11%	0.18
Larch	0%	0.21
	4.5%	0.22
	7%	0.23
	9%	0.24

Wood structures are available in different sizes and shapes. Three of the main types of woods used in constructions are: softwood and hardwood [92].

Table 9-6: Wood construction practices: Hardwood vs Softwood.

	Hardwood	Softwood
Definition	Retrieved from angiosperm trees, has vessel elements that transport water throughout the wood	Retrieved from gymnosperm trees, under a microscope, softwoods have no visible pores because of tracheids.
Uses	High-quality furniture, flooring, long-lasting constructions	Windows, doors, medium-density fibreboard, paper, Christmas trees.
Examples	Example of trees: alder, balsa, beech, maple, oak, walnut…	Example of trees: cedar, juniper, pine, spruce…
Density	Higher	Lower
Cost	More expensive	Less expensive
Growth	Slower rate	Faster rate
Fire resistance	Good	Poor

A research conducted by M. Kozlovska et al. [93] assessed the cost of wood constructions in terms of budgetary index for different types of constructions and building volumes. Table 9-7 summarizes the major obtained findings.

Table 9-7: Cost assessment of different wood construction structures.

Wood structure	Type of construction			Total cost (EUR)	Building volume (m3)	Budgetary index (EUR/m3)
	Number of floors	Foundation	Roof			
House 1	1	Strip	Gabled	83,748	459	182
House 2	1	Plate	Desk	78,600	485	162
House 3	1	Plate	Desk	88,368	434	204
House 4	1	Strip	Desk	93,720	499	188
House 5	1	Strip	Gabled	91,056	506	180
House 6	1	Strip	Gabled	82,596	467	177
House 7	1	Strip	Hipped	10,0680	599	168
House 8	1	Strip	Hipped	97,200	590	165
House 9	2	Strip	Tent	87,960	574	153
House 10	2	Strip	Hipped	201,120	1087	185

10. Bamboo

Bamboo is considered to be among the oldest building materials and is usually compared to other wood and other materials of plant origin due to its advantage. Bamboo adapts easily to large range of different soils as well as climates if needed. In addition, bamboo is considered to grow rapidly and is possible to extract it and use it starting the 4th or 5th year growing year [94]. Bamboo is considered to be a light easily transportable material with a very high resistance per unit mass [95]. Bamboo is a sustainable bioclimatic material and there is an inexhaustible possibility of using its split lamellae, its particles and fibres to create alternative additives or derivative products [96]. Bamboo based materials can be used in modern construction, and its fibres are recycled and used in the pulp industry [97].

The tensile strength of a material is one of the most important mechanical properties for the sizing of structures. The mechanical tests (tension, compression, buckling and bending) make it possible to obtain the ultimate stress (MOR) by type of stress, as well as the Young's modulus (MOE modulus of elasticity).

Obtained findings reflected some trends illustrating the variability of bamboo: density, thickness, diameter, humidity, MOR and MOE in tension, compression and bending. The results of this statistical study are used in order to compare the values found experimentally with those of conventional woods.

Daud et al. [98] investigated in their work the physical and mechanical properties of bamboo material. Table 10-1 summarizes the obtained findings.

Table 10-1: Physical and mechanical properties of bamboo.

Untreated Bamboo				
Bamboo Section	**M.C**	**ρ**	**C.S**	**Shear strength**
Bottom	15.79	0.608	19.96	4.28
Middle	12.50	0.610	23.24	4.56
Top	11.11	0.716	23.80	5.69
Mean	13.13	0.645	22.33	-
Treated Bamboo				
Bottom	25.93	0.785	31.74	3.67
Middle	23.08	0.832	34.71	4.61
Top	16	0.869	36.60	5.21
Mean	21.67	0.829	34.35	-

D et al. [99] in their research also investigated the thermal properties of different bamboo materials, in terms of their thermal conductivity, as reflected in Table 10-2.

Table 10-2: Thermal properties of bamboo.

Bamboo type	**λ**
Uncoated Laminated Bamboo (LB)	0.21 - 0.22
Uncoated Bamboo-Oriented Strand Board (BOSB)	0.24 – 0.27
Uncoated Laminated Bamboo Esterilla Sheet (LBES)	0.28 – 0.33
Indoor Laminated Bamboo Esterilla Sheet (LBES)	0.24 – 0.26
Outdoor Laminated Bamboo Esterilla Sheet (LBES)	0.29 – 0.31
Indoor Bamboo Veneer Board (BVB)	0.33 – 0.36

Bamboo is mostly compared to materials that are plant-based in the industry such as different types of wood used in the construction sector. The above comparison shows the numerous mechanical performances of bamboo faced to tension, compression, and bending, with a relatively low density. Two factors must also be taken into account: low production energy combined with earthquake resistant properties.

11. Cost assessment of bio-climatic constructions

The cost of construction represents a great concern, it must be convenient to the affordability. Bioclimatic materials covered in this report offers remarkable and suitable choices. In a previous research, Dabaeih and Sakr et al. [100] assessed the cost analysis of rammed earth walls in Egypt. Findings showed that rammed earth constructions cost €30 - €40 per m², considered as less than 50% of conventional modern techniques in Africa.

In another study, Dabaeih and Sakr et al. [101] also evaluated the cost analysis of earth bags constructions with a 1-room reference house as illustrated in Figure 11-1. These earth bags constructions were proved to be four times cheaper than other conventional technologies available in the market.

Figure 11-1: Earth bag construction example in Egypt, Africa.

Kuchena et al. [102] evaluated soil blocks as construction materials for rural house models. Soil block walling constructions cost 9,410 MTn, while industrial bricks cost approximately 19,430 MTn in South Africa. This reflects a 53% cost reduction.

An example of cost analysis of clay bricks with additive materials was investigated by Hafez et al. [103] evaluating the unit cost gain potential of modified sand and clay bricks from rice husk waste additive in Egypt. Rice husk waste additive was used in different proportions (5%, 10% and 15%). Cost assessment concluded that the partial replacement of rice husk waste additive reflected a cost-effective gain per brick unit. 5% additive replacement recorded a 14% unit cost reductions, the 10% additive replacement reflected a cost unit reduction by 42.8%, and the 15% rice husk based bricks reached a 25% reduction compared to control samples of clay.

For construction of a building using a straw bale, the cost depends on various factors including; type and time of construction, location, size of building, labour required and accessories. In Italy, the cost of construction of straw bale building – all charges are included – has been estimated to be €1200/m2, which is lower comparing of a normal building with €1500/m2. This difference, which is not large, is linked to the lower cost of materials and to the high cost of labor related to specialized construction [104]. In another economical comparison between a load-bearing wall built with locally produced rice straw bales and a standard load-bearing wall unit built with cement bricks [105], a saving of approximately 10% in the direct cost of the walls is achieved when building with straw bales and an approximate saving of 50% in foundations cost. While, saving in the roofing system exceeds 50% of the total direct cost. At the total, a direct cost saving of about 40% is reached. In addition, the savings generated from the natural insulation provided by straw bale buildings in conjunction with passive solar design.

Table 11-1 shows a comparison in cost between different bioclimatic materials. Only direct construction costs are included such as: foundation, materials, plaster, and labour... except field fees.

Table 11-1: Comparison in cost (excluding tax) between different bioclimatic materials.

Material	**EU**		**Africa**		**Comments**
	Estimated cost of building (€/m2)	Average (€/m2)	Estimated cost of building (€/m2)	Average (€/m2)	
Concrete blocks	55 – 210	132.5	60 – 130	95	Wall building
Rammed earth	250 – 300	225	30 - 75	52.5	300 mm thick wall
Bamboo flooring	60 – 140	100	7 – 28	17.5	
Hempcrete	115 – 155	135	__	__	Wall building
Unshaped stone	80 - 150	115	40 – 70	55	Wall building
Shaped Stone	400 - 700	550	200 – 360	280	Wall building
Load-bearing Straw-bale structure	40 - 100	70	__	__	From the entire area of the building
Cork flooring	60 – 120	90	__	__	

12. Regulations for bioclimatic construction and materials

12.1 Earth standards

After examining 40 different standards of 20 different countries, it was observed that adopted standard documents can be classified into three categories.

- Soil classification.
- Earth building materials.
- Earth construction systems.

In general, there are three types of documents governing the implemented building codes and standards.

- Standards and regulations issued by NSBs (national standards bodies).
- Normative documents issued by local/national organizations.
- Technical documents.

Table 12-1 shows countries with already established building standards and codes for earth and ecological buildings with their respective standard type.

Table 12-1: Countries with already established building standards and codes for earth and ecological buildings with their respective standard type.

Type of standard	Countries
NSB	Brazil, Colombia, Germany, France, India, Kenya, Kyrgyzstan, Nepal, New Zealand, Nigeria, Peru, Spain, Sri Lanka, Tunisia, Turkey, USA (New Mexico, California), Zimbabwe
Normative documents	Australia, Spain, Switzerland, Germany, France is under development

In order to design and implement earth or ecological building codes into national or international standards, the following process of approval should be passed with the National Standards Bodies (NSB). First, the preparation of a draft development by a group of specialists ("the technical committee") with proven competence in building with earth. Second, the prepared draft is presented to a broad range of specialists with a view to reaching a consensus between them. Third, presentation of the "consensus draft" to the NSB for final approval. In Europe, the draft must pass the EC Bureau for Standards for certification. Finally, the publishing of the finalized standard draft in a state decree.

Generally, the parameters covered in earth building standards are:

- Building materials/techniques: adobe, CEBs (compressed earth blocks), rammed earth, timber-framed structures with earth infill.
- Material properties: texture, plasticity/binding strength, natural constituents (organic, lime, salt content), shrinkage, compatibility, classification, test results, safety performance.
- Local conditions: earthquake damage.

Germany was one of the first countries to develop standards for earth and ecological building materials, known as DIN testing standards for different earth-based building materials.

- DIN 18942-1: 2018-12: Building materials in earth – part 1.
- DIN 18945, DIN 18946, DIN 18947, DIN 18948 - Specifies the terms for applying clay building materials.
- DIN 18942-100: 2018-12: Building materials in earth - Part 100 Conformity tests.

- DIN 18945: Earth blocks—terms, requirements, test methods.
- DIN 18946: Earth masonry mortars—terms, requirements, test methods.
- DIN 18947: Earth plaster mortar—terms, requirements, test methods.
- DIN 18948: 2018-12: Clay plates – Requirements and test methods.

Tables 12-2, 12-3 and 12-4 displays the different classes and strength properties of earth blocks, earth masonry mortars and earth plaster mortar building materials following DIN testing standards.

Table 12-2: Brick classes for earth blocks (EB) following DIN EN ISO 7500-1:2004-11.

EB Class	Compressive strength interval value (MPa)
EB2	2.0 - 2.5
EB3	3.0 - 3.8
EB4	4.0 - 5.0
EB5	5.0 - 6.3
EB6	6.0 - 7.5
Test procedure	DIN EN ISO 7500-1:2004-11

Table 12-3: Brick classes for earth masonry mortar (EMM) following DIN EN 1015-11: 2007-05.

EMM Class	Compressive strength interval value (MPa)
M2	≥ 2.0
M3	≥ 3.0
M4	≥ 4.0
Test procedure	DIN EN 1015-11: 2007-05

Table 12-4: Brick classes for earth plaster mortar (EPM) following DIN EN 1015-11: 2007-05.

EPM Class	Compressive strength interval value (MPa)	Tensile strength interval value (MPa)	Adhesive strength interval value (MPa)
S I	≥ 1.0	≥ 0.3	≥ 0.05
S II	≥ 1.5	≥ 0.7	≥ 0.10
Test procedure	DIN EN 1015-11: 2007-05		

Table 12-5 illustrates the area of applications of earth building materials depending on their mechanical strength according to DIN 18945-48 standards.

Table 12-5: Area of applications of earth building materials as a function of their strength following DIN 18945-48.

Brick Class	Area of application
Ia	Rendered, exposed external masonry in fare-faced timber-framed walls
Ib	Continuously rendered, exposed external masonry

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II	Clad or otherwise constructed weather-protected external and internal masonry
III	Dry applications (e.g. deck infill, stacked walls)

12.2 Straw-Bale construction

There are several regulations and standards in the context of straw-bale construction. Some of them are given below [106]:

- BSF-112: Building Science for Strawbale Buildings (USA)
- ICC- International Code Council, 2018 International Residential Code for One- and Two-Family Dwellings- Appendix S: Strawbale Construction.
- 2011- Oregon Residential Specialty Code- Appendix R: Straw-Bale Structures (USA).
- IBC- International Building Code.
- BS 4046:1991 Specification for Compressed Straw Building Slabs (British Standard).

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13. Final conclusion

This work aims to make a state of the art and analysis of bio-climatic materials and eco-friendly construction practices used in Europe and Africa, their processes of obtainment, relative regulations, their quality in terms of performance, affordability and the comfort offered to their inhabitants.

In the current context, materials adapted to local conditions from geological, vegetal and animal origins, that reach the green and bioclimatic concept, are presented. It has been observed the existence of innovative techniques such as hempcrete, straw bales or earth bag construction, as well as ancient materials and techniques such as stone and adobe. The availability and nature of location of the site of building have an important impact on the type of construction itself and its cost. In Africa, the dominant construction practices are based on earth and stone due to the absence of other sources like wood. While in Europe, a variety of techniques are existing.

Besides, the introduction of innovative methodologies for the preparation of these materials and construction with, has offered the possibility to reach the exact same or better performance compared to conventional ones. As an example, use of machines in the manufacturing of different types of "eco-brick" or hempcrete, have reduced the labour which means reduction of total cost.

In the other hand, as it is seen, organizations have been working on preparing necessary regulation to standardize the practices of construction. The example of the "Association La Voûte Nubienne", which is trying to normalize the Nubian Vault method all over Africa. For this purpose, it is recommended from governments and organizations to make much more effort in order to generalize regulations for all types of bioclimatic materials and practices cited in this report.

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