

Characteristics of traditional building materials and techniques based on earth, stone and timber: An overview and focus on Morocco

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Abstract: Traditional buildings are characterized by their simplicity, ideal integration with their immediate environment and cohabitation with the neighboring climate. Thus, they are considered as endogenous constructions. Moreover, traditional building ensures a comfortable living environment for the inhabitants while protecting the ecology. In the aim of providing a global vision of materials and traditional construction techniques most widely used in different regions of the world, particularly in Morocco, as well as the scientific improvements concerning their characteristics, especially mechanical ones. A comprehensive review and bibliographical analysis were carried out using a qualitative approach on raw earth, stones and wood as well as their different construction modes retained. Through this approach, we were able to look at their technical characteristics, the improvements that had been achieved and finally making the necessary recommendations to promote this model of sustainable construction. The general trend is clearly towards improving the mechanical, technical and economic performance of traditional buildings by applying modern techniques and incorporating artificial materials. This multi-scale mixing observed leads us to believe that there is another hybrid approach that emerges in the field of construction. This approach consists of cohabiting the advantages of each of the techniques: the modern one by its better mechanical performances and its economic efficiency and the traditional one by its power of insulation and its ecological and bioclimatic aspect. This approach must be generalized to touch all the aspects of the traditional buildings as the valorization of the technique of roofing by the arches, vaults and cupola with modern technology of the prefabrication and the acceleration of the setting lime by the technology of the carbon cure with the aim of providing us with traditional constructions: ecological, durable, resistant, competitive and good market.

Index Terms: Traditional building; Raw earth; Traditional Plaster; Stone masonry; Arcs and vaulted; Timber dwelling.

I. INTRODUCTION

Traditional construction has advantages and characteristics that make us think of returning to it, at least in villages and communities, and encouraging its use. Earth, stone and wood, natural materials available at zero energy, present excellent ecological and economic performances: local materials available at low cost, ecological, recyclable, hygroscopic and bioclimatic, which integrate perfectly into their environment [1-4]. Nevertheless, the use of artificial materials for construction such as steel and reinforced concrete has caused a breakdown and a lack of know-how [5]. In order to strengthen our knowledge and to build a complete picture of traditional building throughout the world and

especially in Morocco, we propose in this paper to carry out a general bibliographical study on traditional building materials and processes as well as the main research works that have been carried out to finally conclude on the weak points that still need to be improved to make traditional building more competitive and attractive. Thus we have focused on the most used techniques (earth, stone and wood buildings) of traditional construction with the characteristics of their materials and construction processes.

The approach used in this article is a qualitative one based on a bibliographical analysis of traditional construction

technologies throughout the world, with a particular attention to Morocco, as well as a field investigation through a visit to the construction sites of traditional buildings. Through this approach, we were able to look at their technical characteristics, the improvements that had been achieved and finally making the necessary recommendations to promote this model of sustainable construction. The structure diagram of the research content of this work is summarized in Table 1 below.

Table 1
The structure diagram of the research content

Traditional Building Materials and Techniques		
Buildings based on soil	Buildings based on stone	Timber building
-Raw earth -The rammed earth -The Adobe -Cob building -Compressed Earth Blocks -The torchis -Traditional Plaster	-Earth masonry walls -Stones for masonry -Traditional mortar -Kind of stone masonry walls -Mechanical properties of stone masonry units -Arches, vaults and cupolas	-Wood characteristics -Kind of traditional wooden buildings -Wood in traditional Moroccan buildings -Wood durability
Challenges and Recommendations		

II. LITERATURE REVIEW

The materials used in the construction of traditional buildings are natural, it's extracted directly from the immediate vicinity without any industrial processing, we can find:

A. Raw earth

Raw earth (Figure 1) is one of the most widely used traditional building materials in Morocco. Earth is essentially made up of fine soils (clay and silt) with a certain cohesion mixed with sand, gravel and pebbles to limit the propagation of micro-cracks linked to the shrinkage of clay and possibly forced by natural fibers (straw, hemp). Other materials can be added to improve certain mechanical properties (lime to cement the mixture). Raw earth does not require energy for transformation, it is a zero energy material, and nevertheless it tends to lose cohesion in the presence of water. Therefore, it must be protected against any type of humidity.



Figure 1: Raw earth wall, Tiznit Morocco

From a mechanical point of view, the earths used in construction have low mechanical strength; they are generally used for the construction of elements that work in

compression (walls). Their tensile strength is very low, as an example the table 2 illustrates the order of magnitude of their mechanical characteristics, so they cannot be used for elements that work in traction, flexion and shear (beams and slabs).

Table 2
Mechanical characteristics of raw earth [6]

Ramed earth	Compressive strength	Tensile strength	Young's modulus
50% Ramed earth 30% Gravel 4/11 20% Sand 0/4	2MPa	0.2 MPa (Split tensile test)	500Mpa

Soil can be used in many forms for construction, the most used techniques in the world are; the rammed earth, the adobe, the cob building, the compressed earth blocs, and the torchis. It can also be used as plaster or mortar.

B. The rammed earth

The rammed earth is a concrete made of unprocessed earth that has been compressed with varying amounts of clay, sand, gravel, and small pebbles. The materials are placed in a formwork above a base, generally made of stone, to protect it from humidity.

a. Material:

The traditional material used for the realization of the rammed earth is illustrated in figure 2:



Figure 2: Traditional materials for rammed earth construction, Tiznit, Morocco

It consists mainly of:

- Traditional wooden formwork (IFLWAN) 2 m long, 40-60 cm wide and 80-90 cm high.

- Wooden logs (rods and sticks) and ropes are used to fix and tighten the boards.
- The Lmerkz rake: this is the tool used to compact the soil. It consists of a wooden mass attached to a handle. The sole (end, bottom of the mass) exists in several forms according to its use: wide and flat for flat piling, thin and narrower for working the corners of the formwork and the finish.
- Hand tools: pickaxe, hoe and boxes.

b. Procedure:

The construction of the adobe follows the following construction procedure:

- Layout: The trench is laid out according to the previously drawn up ground plans and stakes.
- Excavation: The trench is dug manually to the desired level.
- The stone base (Figure 3): The stone masonry is built to a height of between 50 and 80 cm above ground level. The role of the wall is to protect the raw earth against the capillary rise of water.



Figure 3: Stone base under the raw earth, Tiznit Morocco

- Rammed earth masonry: To place the rammed earth, keys are placed on the rubble wall. The space between the keys is about one meter. Then the panels are placed on the keys. The panels are held in place by rods (three on each side) attached to the ropes. Then we start pouring the carefully moistened earthen boxes. The Maalim (skilled worker) tampers with the earth layer by layer until the mould is well filled and packed. The Maalim (skilled worker) tampers with the earth layer by layer until the mould is well filled and packed (Figure 4).



Figure 4: filling the mould of rammed earth, Tiznit Morocco

- Installation of lintels: Lintels, generally made of wood and stone, are installed at the top of the openings.

- c. Physicochemical characteristics of the soils used for rammed earth:

The clay content in the raw earth for rammed earth should be 10-15% with a moisture content of 14-15%. The proportion of loose soil can contain pebbles up to 50mm [7]. Clays are the fraction of soils with grains < 2 µm in diameter. From a mineralogical point of view there are a variety of clay types, the most common being (Kaolinite, Montmorillonite, Illite, Vermiculite and Chlorites [8]. In the absence of a stabilizer, the clay acts as a natural binder due to its cohesive characteristics. The sand and pebbles represent the inert skeleton of the mixture, contributing to the resistance of the raw earth and stopping the propagation of micro-cracks due to the shrinkage of the clays in the soil.

- d. Mechanical characteristics of a ramed earth wall:

Raw earth walls work in compression. The local compression test carried out on a 1*1*0.2 m³ wall after 150 days of drying reveals a quasi-linear behavior up to 4200 to 4500 daN. Failure is reached at 11000 daN [6]. As their tensile strength is almost zero, raw earth cannot be used for elements that work in tension, shear and flexion (beams and slabs). Studies show that the bearing capacity of soils increases with compaction and the addition of binders (lime or hydraulic cement) and decreases with increasing water content, plasticity index and clay content.

The compressive strength of the soil increases with the cement content, for an optimal water content (Optimum Proctor 7-10% for the study). Table 3 shows the evolution of strength with cement content.

Table 3
Evolution of strength with cement content [9]

Cement content %	28-day compressive strength
5	4
10	8
20	12

Values in Table 2 represent orders of magnitude; they can vary according to the characteristics of the soils and the conditions of the implementation of the formulation.

Some elements are detrimental to the reaction of hydraulic binders: sulphur minerals, micas, organic matter, fertilizers and fertilizer, excessive clay content, nitrogen compounds and phosphates.

Stabilizing low-clay raw earth with hydraulic lime increases its strength. The studies carried out on the effectiveness of lime give very scattered results, this is due to the nature of the soils used and the conditions of implementation even though most studies show a poor gain in strength [8].

The introduction of lime into clay soils causes four types of reaction [10]:

- **Cation exchange:** The dissolution of lime in a hydrated clay soil releases calcium cations Ca^{2+} and hydroxyls (OH^-). The cations are instantly adsorbed and intercalated into the inter-police space of the smectites (TOT structure) and replace the various existing inter-police cations. This instantaneous reaction continues with the addition of lime until the clays are completely saturated with calcium.
- **Flocculation and agglomeration:** This cation exchange leads to a modification of the surface electric charge density of the clay particles and consequently the inter-leaf water layers disappear. This flocculation and agglomeration changes the texture of the clay and improves the consistency of treated clay soils.
- **Pozzolanic reaction:** The dissolution of lime in the soil water (release of Ca^{2+} cations and OH^- anions) allows the saturation of the solution in calcium with rise in pH. In a basic environment saturated with calcium cation, clays are attacked and release alumina and silica which react with calcium in the presence of water and hydroxyls from the lime to form calcium hydrates similar to those of cements (CSH), calcium aluminate hydrate (CAH) and calcium aluminosilicate hydrate (CASH).
- **Carbonation:** Lime reacts with atmospheric CO_2 to form carbonates such as CaCO_3 , MgCO_3 depending on the type of lime used. This reaction causes a reduction in the final strength due to the consumption of part of the available lime for the pozzolanic reaction.

The stabilization of raw earth with hydraulic binders systematically improves its water resistance [8].

Other alternative mineral binders can be used: Sugar cane bagasse ash, Cement dust, volcanic ash, Coal ash, Gypsum, Phosphogypsum, Blast furnace slag and Geopolymer.

Many natural or synthetic organic binders are also used to stabilize soils: petroleum residues, polysaccharides (sugar polymer), algae extracts, cellulose and lignin with animal dung, proteins, lipids and tannins [11].

C. The Adobe

Adobe (Figure 5) is a building material made of soil, water and thatch. The soil used must contain a certain proportion of clay and sand. It is a brick shaped by hand and in a wooden mould in a plastic state and dried in the open air. Castrillo [12], suggest that the ratio clay/silt content for adobe production should be between 5 and 70%. Each component plays a specific role, sand limits the propagation of micro-cracks, clay binds the particles and thatch in its role solidifies the mixture and prevents the appearance of cracks. The dimensions of the bricks vary according to the mould used.

With a mixture consisting of 4.7 % sand, 37.9 % fine sand (20-200 μm) 22.7 % silt (2-20 μm) and 29.9 % clay (<2 μm). K. Dao [13], estimated the compressive strength to be 2.5 MPa and the flexural strength to be 1.2 MPa. The thermal conductivity is estimated to be 1.1 W/ m.K. The stabilization of adobes with cement at the level of 2% stabilizes the adobes

significantly against moisture; however, the compressive strength varies very little with the addition of cement (3.1 MPa for 12% of cements).



Figure 5: Adobe manufactured by traditional methods, Morocco

D. Cob building

Cob building is a traditional earth construction technique used for thousands of years; it consists in building load-bearing walls generally without formwork with a mixture of earth, water and vegetable fibers implemented by successive piling of earth balls in the plastic state. The vertical surfaces of the walls are erected by cutting after a short drying time, while the material is not too hard.

Typical soil for making the cob consists of about 30% gravel (> 2mm), 35% sand (0.063/2 mm) and 35% silt (0.002/0.063 mm) and clay (< 0.002 mm = 2 μm), with a variation of $\pm 10\%$ [9]. Clay as for other raw earth constructions plays the role of binder for the other components (sands and gravels), if the clay content is low there will not be enough binding between the soil particles, a minimum water content of 15% is put forward by Akinkurolere [15]. Moreover, high clay content can lead to drying shrinkage of the material and cracks that can weaken the material. Specialists recommend clays with stable structures such as kaolinite and illite [14].

For the implementation of the Cob, certain plasticity is recommended to facilitate the implementation. Houben and Guillaud [16] Recommends a water content of 15-30% for the application of the cob.

Coarse grained soils represent the inert skeleton that gives strength to the material, a continuous granulometry is recommended (Uniformity Coefficient >2) to increase the compactness of the mixture and therefore its strength.

Fibers act as reinforcement for composite materials such as a cob. They are available at low cost. The use of plant fibers allows the reduction of environmental impacts compared to the use of polymer fibers because they are renewable and CO_2 neutral [17].

Fibers can be grouped into three categories: mineral fibers, animal fibers and plant fibers [14]. The role of the fibers within cob walls is to [18]:

- Make it easier to mix and handle.
- Accelerate the drying process.
- Distribute shrinkage cracks throughout the wall mass.
- Improve the cohesion and shear strength of the wall.
- Improving weather resistance, reinforcing the corners of the walls.

Tuan [14] Demonstrated that the mechanical behavior of the material depends on the direction of load application. If the load application is in the direction of compaction, it contributes to the rise in stress because the fibers resist against fracture propagation caused on by tensile stresses. In contrast, if the load is applied perpendicular to the direction of compaction, the compressive strength is reduced (On average 1 to 4 MPa for compressive strength and less than 1Mpa for tensile strength). In general, the introduction of plant fibers decreases the mechanical performance due to the decrease in density of the material.

E. Compressed earth blocks (CEB)

The CEB is a recently developed technique, around the 1950s construction with this technology started. A lot of research work has been done in order to understand the subject. CEB is obtained by statically compacting a quantity of soil in a mould of given dimensions. CEB can be stabilized with lime, cement and bitumen. CEB is laid with the aim of using local materials [19]. The performance depends largely on the nature of the soil used, the conditions of implementation and the stabilization materials.

According to the French Association for Standardization, the soil should not be too plastic to limit cracks in the CEB and must have a minimum of cohesion when it is compacted. The grains must not exceed a size limit depending on the size of the blocks (average 5mm) [20].

The strength value of masonry walls can be estimated from the characteristics of the CEB blocks and the mortar used as illustrated in table 4:

Table 4

Characteristic compressive strength of masonry [21]

f _k (Mpa)		Compressive strength of mortar f _m (Mpa)		
		2.5	5	8
Types of CEB	CEB20 (2MPa)	0.97		
	CEB40 (4MPa)		1.93	2.22
	CEB60 (6MPa)		2.56	2.95

The application of very high compaction stresses allows improving the mechanical performance of CEB (Compressive strength 4.1 to 10.2 MPa and Young's modulus 1500 to 4000 MPa) [22].

Numerous investigations on the stability of CEB have been conducted, including the most recent studies by Tran [23] and Sore [24]. The results obtained differ from one study to another depending on the nature of the soil, the cement content and the curing conditions. For the Tran research [23], there was a noticeable increase in strength from 0.6 MPa for 0% cement to 6 MPa for 12% cement. According to Sore [24], strength increased from 1.4MPa for 0% cement to 8.2MPa for 8% cement. Studies [8] have revealed a definite resistance to water despite the absence of international standards for the durability of CEB bricks.

Studies on CEB stabilization with lime demonstrate that the strength only slightly improves [25, 26]. To reduce the

content of cement and lime studies propose to valorize low carbon footprint pozzolans and industrial by-products (coal ash, sugarcane bagasse ash or cement kiln dust). The amounts of binders utilized appear to be substantial (up to 20%), despite the fact that these solutions are thought to be less polluting than cement and lime alone [8].

The stabilization of CEB using organic binders has been chosen by studies. The majority of the time, organic binders and activating agents are employed together. In general, this type of binder results in modest strength increases [8].

F. The torchis

A filling complex made up of a combination of building soil, plant fibers, and water that is fastened to wooden and/or plant fiber supports is referred to as wattle and daub material. Although the amount of mixed plant fibers varies widely from wattle to wattle, the content is uniform throughout a panel or the area between its corners. This ratio is established in accordance with the precise goals of what needs to be done [27]. To shield the wood/earth structure from moisture, wattle and daub is always constructed on top of a masonry wall.

The daub does not have a load-bearing role; it just fills the space between the timber frame elements and provides thermal and acoustic insulation [16]. In the north of France, a mixture of clay, straw and water is used for the wattle, the construction method depends on the nature of the timber frame used [28]. The roof is supported by the timber frame through horizontal lathing. Timber framing varies between regions according to the type of wood used, the type of assembly and the spacing between elements [29].

G. Traditional plaster

Plaster is a paste-like mixture that is used to cover a rough masonry wall, also known as a substrate, in order to give it generally uniform and flat surface, as well as possibly other characteristics. This is done on the outside to protect from external factors and frequently to provide a uniform facing of a decorative nature. In the latter case, plaster is concerned with comfort and also protection.

a. Functions of plaster

Depending on their nature, exterior plasters perform one or more of the following three functions:

- Dressing: by making up for irregularities in the structure. Its smooth appearance favors run-off.
- Protection: by ensuring the waterproofing of the wall, while allowing the support to "breathe".
- Decoration: by giving the final appearance of the façade. This function brings an important aesthetic aspect to the façade through its composition.

b. Type of traditional plasters

- Earth and straw plasters: are made of two natural materials which are the most easily usable by humans: earth, which must be sufficiently clayey without being completely so, and straw, It can be obtained from any straw cereal

cultivated in these regions and used to make plaster (wheat, barley).

- **Lime plaster:** Lime plasters (Figure 6) are made of two natural materials: lime and sand. Depending on the clay content during the firing of the calcite, a distinction is made between two types of lime : Air lime, where the setting takes place by carbonation in the presence of water (water vapor reacts with CO_2 to form carbonic acid H_2CO_3 , which in turn reacts with calcium oxide to form limestone again, this reaction is very slow given the low percentage of CO_2 in the air 0.04 % and hydraulic lime or calcite combined with silica and iron and aluminum oxides form unstable anhydrous minerals (silicates and aluminates of lime) which form a paste in the presence of water capable of setting and hardening progressively, it is the hydraulic type setting which characterizes the beginning of the lime setting, a second relatively slow air type setting continues in contact with humid air where the lime carbonates[30]. The role of sand is to limit the shrinkage and cracking of the mortar.



Figure 6: Lime-based plaster, Tiznit Morocco

- **Tadlakt:** an ancestral Amazigh know-how (waterproof and antibacterial coating used as paint made from lime, coloured pigments and black soap, with olive or linseed oil). It is traditionally used to waterproof pieces in contact with water. For generations, it has served as the region surrounding Marrakech's architectural trademark [31]. Historically, Marrakech lime produced by traditional processes has been used since the twelfth century for the production of tadelakt lime plaster.

H. Traditional stone masonry

Stone masonry walls (Figure 7) are made of stones and mortar. The stones are assembled layer by layer; the two faces of a wall are regularly connected by breezeblock blocks, i.e., long stones passing through the wall from side to side.



Figure 7: Traditional stone masonry, Morocco

Stones for masonry: Rocks originate in the earth's crust. Their characteristics vary according to type, origin and formation mechanism: igneous rocks, sedimentary and metamorphic rocks. Due to their low cost, high durability, and ease of use, they are among the most extensively used materials. Stones are characterized by their physical (bulk density, size coefficient, porosity, capillarity, absorption coefficient and gelocity), mechanical (compressive strength, tensile strength, sound propagation velocity, wear resistance, impact strength, and modulus of elasticity) and thermal (thermal conductivity) properties. A set of tests are detailed in the French standard NF B10-601 to determine whether stones are suitable for use in construction.

Natural stones have a wide range of porosity and mechanical characteristics. In general, the strength of stones decreases with increasing porosity. Magmatic rocks are stronger than sedimentary rocks, but difficult to work [32].

Traditional mortar: Mortar fills the joints between the blocks of the stones, ensures the adhesion between the blocks and the mechanical linking between the blocks. Mortar is a mixture of water, aggregates (often sand) and a natural or artificial binder. In order to stabilize the brickwork, it fills the spaces between the joints and acts as a link between nearby blocks. The joints are always considered as the planes of weakness from a structural point of view of the masonry, so they must be staggered between contiguous courses to have a more resistant layout. The mortar also ensures that the structure is watertight and prevents punching between the blocks.

The binder can be clay, lime (air binder), cement (hydraulic binder) or bastard mortar (lime with cement). The role of the binder is to provide strength to the mortar and to bind the mortar components together. The sand is used to give consistency to the mortar, it allows a better workability, reduces costs and shrinkage. According to Domone and Illston [32], the mortar should not contain sand grains with a diameter greater than half the thickness of the smallest joint. The sand used should have a continuous granulometry range to achieve a stronger compact mortar. Fine sand requires more water for mixing so the strength decreases and the shrinkage increases [33]. The choice of mixing water is also very important, as it is the key to setting the binder mixed with the sand. It should be as pure as possible. Drinking water can be used without danger. It should not contain any organic or earthy matter, or industrial waste (acidic water, etc.). Sea water should be avoided if the binder has high free lime content.

Kind of stone masonry walls: Stone masonry walls can be classified according to their form: rubble masonry and ashlar masonry. The stones can be bonded with mortars, so multiple combinations are possible depending on the type of joint, bonding and the stone's surface's quality of finish; they can also be superimposed without binder (dry stones). Transversely the rubble masonry wall can be composed of a

single row of stones superimposed on each other (single leaf). It can be made up of two fully distinct rows of stones joined together by mortar or by stones of various sizes (double leaf). It may be made up of two rows of large stones spaced apart by a row of heterogeneous, thin stones, while the rows may occasionally be joined (three leaf) [34]. If the assembly is irregular, it is called "blocking"; elements of different shapes and sizes thrown into a mortar bath, the blocking can be used as a structural element or as a filling element between facings. If the assembly is regular, it is called a "fitting". The bonding can change from one region to another, depending on the size of the stones; a distinction is made between small bond, medium bond and large bond masonry.

Confined stone walls: This technology, which is beginning to be, used more and more, has many advantages: it is climate-proof, bioclimatic, economical and easy to install. To build a CSW wall you have to: collect the stones, braid the galvanized steel wires, make the cages, assemble the cages in rows, fill the cages with stones, insert the carpentry, plaster the walls and lay the roof [35].

Mechanical properties of stone masonry units: The masonry can be surrounded by chains and reinforced with steel or composite materials to improve its mechanical performance. Due to its vulnerability to large repeated and dynamic loads, more research must be done before it may be used in seismically active places.

To determine the mechanical behavior of rocks, several approaches are possible: the so-called global approach aims at apprehending the global behavior of the masonry (failure criteria) without directly focusing on the local behavior. Other works focus on the behavior of each element (stone and mortar) to deduce the global behavior of the structure (multi-scale analysis).

Eurocode 6 specifies the formulas for calculating the short-term elasticity modulus $E = f_k \cdot 1000$ and the shear modulus $G = 0.4 E$ (this formula overestimates the value of G [36]).

Masonry has a very good compressive strength. Historic buildings were built in such a way that the masonry works in compression (load-bearing walls, arches and vaults). The formulas for checking masonry based on the limit state approach are proposed by Eurocode 6. The compressive strength can be determined by the standardized test [37]. However, specimens are difficult to produce and therefore tests on stacked blocks are often carried out even though the results may be slightly different. The mechanical properties of stone masonry depend on the mechanical properties of the stones and mortars. In general, the masonry assembly is less strong than each individual element [38], the assumption that the strength is bounded between the lowest and highest strength remains true when the difference between the two strengths is very large.

The tensile strength of masonry is still low and often considered to be zero. Nevertheless, it is an important parameter to take into consideration for walls that work in

bracing. According to Backes [39], two cases of cracking are possible for tensile strengths parallel to the setting layer: an almost vertical failure when the tensile strength of the bricks is low, or cracking along the joints when the tensile strength of the bricks is much higher than that of the mortar (case of stones).

I. Arches, vaults and cupolas

The system of construction in arches and cupolas is a thousand-year-old technology used since the 3rd millennium BC in the countries of the Middle East and in Egypt. Later the Sassanian, Romans, Byzantines and Muslims used them before being used in Europe. This technology can be adapted to any building program regardless of the scope. The materials used in the construction of arches, vaults and cupolas are diverse and depend on several parameters; the availability of materials, the geometry of the site, the construction method, the loads, and the environment. These include masonry, stone, timber, steel and concrete constructions.

Arches: Is an arch-shaped construction whose ends will rest on solid points. The arch is made of stone, rubble, brick, concrete, steel or wood assembly. The arched shape allows loads to be transmitted to the ends. The design of the arches aims to find a geometry for which the material works mainly only in compression by limiting the shear forces and the flexing moments which must be zero (the funicular polygon).

Vault: Is a curved masonry work to cover a space by leaning on walls, pillars or columns, the vault is made by a floor of (brick, rubble, stone and concrete) built on arches (intrados). The upper part is called extrados. When the height is less than half the width, the vault is called "low" and when the height of the vault is greater than half the width, the vault is called "high".

Unlike arches, which can be assimilated to a line, vaults can be assimilated to a surface. There are several types of arches depending on the way the loads are transmitted:

- **Corbelled vaults:** Made of materials piled up in successive rows, the upper part is in advance of the lower part, stability is ensured by an overload of weight on the back of the elements.
- **The arched vaults:** The vault works like an arch. The vertical loads are balanced by compression of the elements of the vault. The forces of the vault must be taken up at the right of these supports which implies the presence of thick walls (Romanesque architecture). They are also called form structures because they mobilize the form to balance the loads. For the masonry vaults, a trapezoidal cut stone layout and specific counterbalancing elements are used [40]. The double arcs allow the vaults to be reinforced and the filling to be lightened with a decorative aspect.
- **The ribbed vaults:** originating from Gothic architecture; the vaults rest on the ribbed vaults (diagonal ribs of the middle Ages) which are crossed and rest on pillars. The effect of the thrust can be taken up by the load-bearing

walls in the case of the curved vault, often reinforced with 8 toric ribs, whereas the flat vault requires the use of buttresses [40].

- Ridge vaults: The shapes of the vaults obtained by the intersection of two cradles, the effects of mass are localized on the isolated supports (Romanesque and Oriental architecture) [34]. The ogival vaults allow the reduction of the thrust of the vaults by 50% compared to the groin vaults (ogival forms with lightening of the filling) [40].

Cupolas: an inverted vase-shaped arch with a semicircular, parabolic profile and a circular, elliptical or polygonal plan. The plane on which it rises may be circular, elliptical, square or polygonal. Domes and cupolas are sometimes associated, but each fulfils a different role the "dome is a component of the urban landscape, the cupola a centralized interior space" [41]. The articulation is important between the cupola and the supporting walls. The ancient Roman architects avoided building on squares; they built directly on circular walls [42]. The Byzantines, inspired by the Syrians and Persians, built the cupolas on pendentives (a curved triangle that starts from the square and flares out to ensure the circular shape on which the cupola rests).

J. Timber building

In traditional construction, wood is the third most common material used after soil and stone. The environmental impact is lessened by using wood. It is a renewable resource that naturally absorbs CO₂ (45g per 100g of dry matter on average) [43], requires less energy, results in less water and air pollution, and has a low global warming potential compared to modern building materials (emits six times less greenhouse gases than concrete and four times less than steel during the material's life cycle) [44].

a. Wood characteristics:

Wood is a material of organic plant origin consisting essentially of the trunk cells of woody plants. The species of woody plants fall into two main categories: softwoods (Spruce, Pine, Larch, Arolla, Fir, Spruce, White Pine) and hardwoods (Oak, Maple, Ash, and Beech).

Wood is mainly composed of celluloses (C₆H₁₀O₅) (40 to 47%), hemicelluloses (C₆H₁₀O₅) (25 to 35%), lignins (C₆H₁₀O₅) (16 to 31%), extractives (rubber, resin, fat and sugar) (0 to 10%) and minerals (Ca, Na, P, K, Mn, sometimes Silica and CaCO₃ such as Iroko) (< 5%) [44].

Naturally the woods are acidic (PH 4.5 to 5.5 and can reach less like Eucalyptus, Oak and Cedar). The acidity is due to the formation of acetic acid C₂H₄O₂ by the hydrolysis of the acetyl groups of hemicelluloses. The wood also contains the formic acid CH₂O₂ in small quantities [45].

The cell wall is the wood fiber composite indeed; the hemicelluloses are associated with the celluloses to form the microfibrils, the lignin form an outer protective band and bind

between the microfibrils to give the wood composite shear strength. The gradual transition of crystallinity from the fiber to the matrix results in high inter-laminar shear strength.

Wood texture depends on the size of the cells and their arrangement; when the dimensions or wall thickness of the cells remain uniform (Beech or Yellow Pine) through the growth ring, the texture is uniform. Texture is said to be uneven when there is a change in cell characteristics across the growth ring.

The wood figure refers to the ornamental marks observed on the cut surface of the wood; these marks depend on the structural characteristics of the wood (grain, growth rings, rays and knots). If the conductive elements are very small, the wood is said to be coarse-grained and if they are distinct to the naked eye, the wood is said to be coarse-grained. The significant change in cell size corresponds to heterogeneous grains as opposed to homogeneous grains where the size remains constant.

When a change is produced in the growth rings regarding cell distribution or cell wall thickness, distinct grain patterns will appear on the machined faces. On the radial surface of the wood, the rings are parallel and vertical to each other, on the tangential face a series of concentric arcs is produced and on the transverse plane (end grain) concentric circles with the pith as the center characterize the wood.

The deposition of the colored extracts in the heartwood gives it its coloring. Wood that does not contain extractives is not colored, such as Spruce and Ash. Fungi also contribute to the coloring of the wood.

The density of wood is a function of its microscopic structure and the presence of extraction products, which generally represent less than 3% of the dry mass of the wood, but can reach 10% for certain types of wood [45]. The value of the humidity influences the density of the wood, increasing the mass and the volume at the same time. For wood used in construction, the moisture level quoted is usually 12%. The volume of the cells, their thickness, the presence of extracts and the humidity make the density vary significantly from one type of wood to another. For moisture content of 12% it ranges from 176 kg/m³ for balsa to 1230 kg/m³ for lignum vitae. Each type of wood has an average density reflecting the difference between pith and outer rings and between trees on the same site.

The dimensions of wood change with humidity and temperature, wood is a hygroscopic material, the humidity of wood depends on the water vapor pressure and the surrounding temperature; this is the equilibrium water content of wood. For living wood the water content is important, it varies from 60% to 200%, the water occupies the cell cavity and the interior of the cell walls. At moisture content of more than 20% the wood is susceptible to fungal attack, so it is necessary to dry the wood after felling before use [45]. During drying the shrinkage of the wood can be considerable, its value changes according to the three axes;

it is more important in the tangential and radial (transversal) direction and negligible in the longitudinal direction.

The behavior of wood with respect to loads depends on several parameters such as its density, the direction of the load with the wood grains, the direction of the wood fibers as well as the temperature and the degree of moisture. Wood has a viscoelastic behavior; the application of the elasticity theory can be applied provided that the appropriate safety factors are taken into consideration. For small loads, wood has a curvilinear elastic behavior. The elastic limit of wood in bending is limited to 60% of the breaking limit and its elastic limit in compression varies from 30 to 50% of its breaking limit depending on the type of wood. Increasing temperature induces a higher creep response [45]. Also, increasing moisture content increases the deflection of wood considerably. Wood has a high bending strength, as well as compression and tensile strength. The values of the breaking point vary from one wood to another depending on these characteristics.

b. Kind of traditional wooden buildings:

Hut (Figure 8): A rudimentary shelter made from a framework of bamboo thatch or wood logs filled with bamboo, bushes, straw or a combination of these materials that also serve as a roof for the structure. The first structures were found in Asia, Africa and America [46].



Figure 8: Zulu Hut, Zululand South Africa [47]

Log home (Figure 9): A traditional technique used in regions with high forest density, it consists of making vertical walls (load-bearing, separating and insulating) out of solid wood by stacking pieces of wood (logs, planks) horizontally. The pieces fit together perfectly to ensure water and air tightness. The pieces are crossed at the corner or assembled in dovetail. A lining can be associated in order to reinforce the waterproofness of the walls. The roofs are built according to the traditional techniques of the realization of the wooden frames. It is essential to take into account the important settlements of the walls due to the transverse compression and the retractions of the logs. The massive wood has naturally a good thermal insulation and brings a good hygrometric comfort and a natural renewal of the air [48].



Figure 9: Stacked log loft (1193), Rilag, NORWAY [49]

Wattle and daub (figure 10): this is a house made with a wooden or bamboo frame forming the framework of the wall. The wall filling is made from a mixture of mud, manure, straw and sand. The walls are usually built on a masonry base to protect the structure from rising damp. The bracing of the timber frames is achieved by means of sloping pieces of wood called "curved braces". It has been used for 6,000 years, taking advantage of the abundance of raw material [50]. A distinction is made between the half-timbered structure by the long timber method where the structural posts are contained from the ground to the roof (a relatively old technique) and the short timber structure where the posts are the same height as the floors.



Figure 10: Half-timbered house Bourgogne France [51]

Timber frame houses (Figure 11): Timber frame construction allows for the construction of sturdy houses made from self-supporting timber structures fixed with connections between the elements. Traditionally the timbers were joined by hand-made "mortise and tenon" joints. Lightweight framing techniques have been used in the USA since the 19th and early 20th centuries: Balloon framing is the construction of a full-height timber wall frame for a two-story building. Since the middle of the 20th century, platform framing has dominated the timber construction market, where each story is built on top of the other using short framing [52].



Figure 11: Balloon framed house USA [53]



Figure 14: Roofing system based on earth, stone and wood (Mountainous area Morocco) [54].

c. Wood in traditional Moroccan buildings

Wood is used to make the traditional lintels under the slopes, also for the manufacture of traditional Lintels doors and windows (Figure 12).



Figure12: Traditional wooden lintel, Tiznit, Morocco

The traditional Moroccan roofing (Figure 13) framework is made of wood, the simplest system is composed of logs placed on the walls, the joists (tree trunks with a smaller diameter) rest on the logs and the walls, then the system is covered with a layer of reed and possibly with thatch ensuring the connection between the elements of the framework, a plastic film protected by a clay soil ensures the waterproofing of the system.



Figure13: Traditional wooden floor Tiznit, Morocco

In the Moroccan mountainous areas where the climatic conditions are difficult, the final roofing differs to give the construction the desired level of insulation and waterproofing (Figure 14) ; The first variant consists of layers of earth, stone and thatch laid on the wooden system, the second variant is made of flat stones fixed to the roofs by a layer of earth on a stone filling, the whole is laid on the wooden frame to ensure thermal insulation, finally the third variant is characterized by the presence of a zinc sheet laid on rafters by means of nails, the whole is fixed on the same roofing system.

d. Wood durability:

The durability of wood reflects the ability of wood to resist chemical, physical and biological attacks by aggressive agents. From a distance wood is attacked by biological agents; fungi and insects can cause enormous damage to wood. In the absence of aggressive agents and fire the wood can last even for long periods (thousands of years depending on the species).

Wood exposed to light energy deteriorates (photochemical degradation). Rain and wind also lead to a complex degradation process that gives the wood a silvery grey appearance. Ultraviolet light causes lignin degradation and visible light causes shortening of the cellulose chain length. The process of photo-degradation of wood is very long (1mm in 20 years) [45]. However, in order to protect the degraded wood from biological agents, it is important to replace the damaged wood.

Wood has a very good resistance to many chemical agents such as acids, but the action of alkalis, even in diluted form, causes the lignin and hemicellulose to dissolve. The acidity of the ferrous salts (very acidic) in the presence of humidity attacks the wood and causes softening and a dark blue coloring around the steel nails.

Mechanical performance of wood decrease with increasing temperature. The high temperature causes a browning of the wood associated with a caramel (burnt sugar) smell. This decrease is due to the degradation of the hemicelluloses and even with time the cellulose is affected by reducing the chain length.

Under permanent loads for long periods (creep), wood loses its mechanical performance. For example, for a 50 years load, wood can lose 50% of its bending strength [45]. In addition, the stiffness decreases which increases the value of the deflection with time. The effect of creep must be taken into consideration when designing timber structures [45]. The effect of compression under excessive stresses on wood can degrade the strength of the cell walls and lead to a loss of strength and toughness.

The resistance to biological agents depends on the type of wood. Although it is a biological material, wood can resist insects and fungi for a long time. This resistance is due to the composition of the cellulose walls (presence of lignin) and the deposition of extracts. The attack of wood-eating fungi can

only be triggered in the presence of a moisture content of more than 20% [45]. The low percentage of nitrogen in the wood slows down the propagation process of the fungi.

In general, the heartwood is more resistant to insects than the sapwood. Even the heartwood can be attacked in the presence of decay. Wood-boring insects and termites are the main predators of wood. Wood used in the marine environment can be attacked by beetles and caddis flies.

Wood is a combustible material which allows flame propagation and heat release, however wood compared to steel allows better maintenance of mechanical performance with increasing heat.

III. CHALLENGES AND RECOMMENDATIONS

The world is currently facing a climate change that is negatively impacting life on earth due to the rise in global temperature. According to a BIMhow study, the construction sector is responsible for 23% of air pollution, 50% of climate change, 40% of drinking water pollution and 50% of landfill waste. In addition, it is also responsible for 40% of global energy consumption (USGBC) [55]. The consequences of this change can be catastrophic for humanity and the earth if effective and corrective measures are not taken to avoid reaching tipping points. Aware of this issue, the scientific community has initiated efforts to develop ecological alternatives to reinforced concrete, the main source of pollution in the building industry, through the enhancement of traditional techniques by modern technologies. The achievement of the objectives requires in addition a perfect mastery of materials and techniques of sustainable construction and the development of new techniques capable of making the traditional more competitive and profitable without touching its hygroscopic and environmental aspect in order to overcome the technical and economic barriers which slow down the promotion of this model of buildings.

Many efforts have been made by the scientific community to improve the mechanical characteristics and water resistance of raw earth. The techniques used have focused on three main methods; either the stabilization of the earth by binders (lime, pozzolanic addition, cement, bitumen, mineral and organic binders), or the stabilization by fibers or the combination of the two previous methods. Mechanical techniques as for the compressed earth brick have been used for the improvement of the mechanical characteristics of the raw earth as for the compressed earth brick. Despite the gain in strength and the systematic improvement of water resistance, the use of binders with high carbon footprints such as cement raises the question of the ecological usefulness (main cause of recourse to the material) of these practices [56], hence the need to take into account the ecological component in the studies conducted on the stabilization of raw earth. In addition, the high content of stabilizing elements decreases the hygroscopic aspect of raw earth [57], so it is necessary to decrease the content of stabilizing elements in order to preserve this property, which is a main characteristic

of traditional buildings [30]. The stabilization of raw earth by mineral additions resulting from the valorization of industrial by-products seems to be more relevant from an ecological point of view, but the relatively high incorporation rate and the relatively low setting speed [58, 59 and 60] present real obstacles for their exploitation. The thermal conductivity of raw earth, as for other materials, does not depend in general only on the density of the material, so the incorporation of stabilizers can affect this property by increasing the density of the raw earth [61]. The studies must be continued with the objective of determining the optimum rate of stabilizers to be incorporated that guarantee the minimum required without being able to affect the ecological aspect, main cause of the recourse to the traditional in the field of the construction. Other tracks have been inventoried as the stabilization by organic binders seems to give encouraging results, for example the Ovalbumin that does not require pre-activation [8], nevertheless with the important quantities requested for the construction does not seem cheap solutions especially with the increase of the demand on the food and the climatic changes that impact the agricultural production, from where the need to think of developing solutions of stabilization outside the materials of first necessity for the man.

Lime is one of the vernacular materials that have been used historically for the production of mortars necessary for the binding of masonry elements or for plastering works. It was also mixed with natural pozzolans such as fly ash to produce the Roman concrete [62]. Moroccans mixed Marrakech lime with black soap to produce a special plaster used to waterproof bathrooms [63]. After the discovery of portative cement in the 18th century [64], the use of lime became marginal despite the hygroscopic and ecological advantages it presents. The setting rate of lime is relatively slow which presents a real obstacle to its ecological valorization in construction. The technique of carbon cure widely tested on concrete based on Portland cement [65, 66 and 67] seems to be more suitable for its use in improving the setting of hydraulic lime because it contains a higher percentage of carbon dioxide capable of reacting with CO₂. In addition, studies carried out on the curing of lime under high carbon dioxide curing conditions show a clear improvement of the setting [68].

It is well noted that the construction techniques used for traditional construction techniques are still delayed compared to modern technologies of reinforced concrete buildings, which is one of the major barriers against their promotion, so it is important to apply modern processes on traditional buildings to increase their competitiveness. For example, the techniques of realization of slabs and floors by vaults and domes have been abandoned to the detriment of modern techniques easy to implement and cost-effective based on reinforced concrete. The important constraint linked to the realization of this model of floor is the difficulty of implementation what increases their cost price. The valorization of these vernacular techniques is possible thanks

to the modern techniques of prefabrication by minimizing the time of realization and the cost [69]. The vault elements will be prefabricated in the factory and put in place with the help of lifting equipment. The prefabrication allows increasing the production rate and eliminating the difficulties related to the formwork implementation necessary for the realization of the masonry of the vaults and cupolas.

Traditional building materials (earth, stone) are known to be seismically vulnerable due to their low resistance to shear forces [70]. The constructive dispositions improve the anti-seismic behavior of the traditional buildings against the earthquake without guaranteeing a sufficient protection against the violent earthquakes. The incorporation of manufactured materials such as steel, carbon or glass bars can affect their ecological and environmental qualities. Hence the need to think of innovative solutions capable of guaranteeing the desired level of protection without impacting their environmental qualities. The philosophy of design of structures against earthquakes is based on the attribution to the structures the level of resistance and rigidity desired to resist the seismic forces and remain in the elastic domain for moderate earthquakes and in the case of violent earthquakes also confer to the structure the level of ductility capable of making the material work in the plastic domain without failing [71]. From the analysis of the works carried out on the stabilization of raw earth, it turns out to be very difficult to give the stabilized earth the necessary and sufficient resistance, hence the need to think of giving the material more ductility capable of dissipating the seismic energy. The work carried out on the recovery of waste tires in concrete confirms a clear improvement in the ductility of the material [72]. The application of this technique on earth or lime concrete can give encouraging results by improving the capacity of the materials to dissipate energy. This technique has two major advantages: recycling tire waste in the building industry and improving the ductility of the materials.

In spite of the ecological and technical advantages that wood presents, a green, carbonivorous and recyclable material with better mechanical performances and an adequate normative framework, the high demand and the limit of the reserves intended for the construction have generated lately an important increase of the prices. Therefore, the use of wood in construction is mainly linked to availability constraints, hence the need to set up an efficient forestation policy at the international level.

Traditional materials and constructions may be ecologically interesting, but their poor mechanical properties limit their use to rural areas or areas where building densities are lowest. The high-rise buildings and residential towers that dominate city centers can only be built using modern construction materials and technologies. It is for this reason, and with the aim of limiting the impact of construction in its entirety on the environment, that Belabid & al [73] in their

article "the concept of hybrid construction technology; state of the art and future prospects", via an analysis of sustainable construction techniques and reinforced concrete buildings, propose opting for a third way, which is hybrid construction. This new approach allows construction, environment and economy to coexist in a single building model, making our cities much more resilient.

IV. CONCLUSIONS

Geosourced materials (earth, stone and lime) and biosourced materials (wood, natural fibers) have been the basic building materials since the first civilizations. These materials have always demonstrated their ecological and environmental qualities compared to industrial materials (ecological, good thermal insulation, good hygrometric regulation, fire resistance, 100% recyclable, competitive). In spite of these interesting advantages, they also have disadvantages (poor mechanical characteristics, need for periodic maintenance and rapid degradation over time, poor water resistance, poor resistance to earthquakes and biological attack (wood)). The evolution of ecological construction is limited by the absence of regulations, the absence of calculation standards and the lack of know-how. The research work that has been carried out on an international scale on eco-materials has made it possible to improve their mechanical performance and their resistance to water; either by stabilization operations through the addition of binders and fibers or by mechanical processes (CEB and CSW). In spite of the importance of the work carried out, it can be seen that the proposed ecological models do not yet compete with modern constructions in terms of mechanical performance, rate of construction and efficiency. That is why it is necessary to think about developing hybrid construction models that will allow the advantages of each of the known construction methods to coexist; the modern one for its better mechanical performance and its economic efficiency and the traditional one for its insulation power and its ecological and bioclimatic aspect.

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CONFLICT OF INTEREST

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