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LE VILLAGE

RESEARCH ON RAW EARTH BIO-BRICKS FOR THE DESIGN OF A SCHOOL IN SENEGAL

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ABSTRACT

This study investigates the use of compressed earth blocks, consolidated with vegetal fibres, as a building material. The aim is to analyse and confront the physical properties of raw earth bio-bricks with their environmental impact. The thesis is organised around the specific case of an architectural project for a school in Casamance in Senegal.

The design project was inspired by the 2023 Kaira Looro competition created by the Balouo Salo charity. The competition subject was the creation of a school for the rural region of Casamance in the South of Senegal. The social ambitions of the project were the creation of inspiring educational spaces, the provision of health and hygiene facilities and the involvement of the local community in the life of the school. Another important objective was the design of spaces adapted to the local tropical climate whilst having minimal environmental impact. For this purpose, the design is based on natural and reused materials and follows bioclimatic strategies. The key concept was inspired by the typical structure of Casamance villages, introducing multiple units converging into multi-purpose outdoor spaces.

The research on bio-bricks was conducted through a literature review and experimental tests. Three different types of vegetal fibres were tested: bamboo, straw and wood fibres. Tests samples were produced using manual presses in the laboratory of structural materials of Politecnico di Milano in Lecco. The compressed earth blocks were then submitted to erosion and compression tests in laboratory. To determine the environmental impact of the bio-bricks a comparative Life Cycle Assessment was carried on both building and structural elements.

The study revealed that raw earth bio-bricks constitute a low-emission structural material in comparison with other widespread load-bearing options. In particular, the use of bamboo fibres resulted in the best mechanical and environmental performance. Ultimately, this project demonstrates through a case study that compressed earth bio-bricks can be a component of high-quality sustainable building design.

Questo studio analizza l’uso di blocchi di terra compressa, consolidati con fibre vegetali, come materiale da costruzione. L’obiettivo è quello di analizzare e confrontare le proprietà fisiche dei bio-mattoni in terra cruda con il loro impatto ambientale. La tesi è organizzata intorno al caso specifico di un progetto architettonico per una scuola in Casamance in Senegal.

Il progetto di design è stato ispirato dal concorso Kaira Looro 2023 creato dall’associazione Balouo Salo. Il tema del concorso era la creazione di una scuola per la regione rurale di Casamance, nel sud del Senegal. Le ambizioni sociali del progetto erano la creazione di spazi educativi stimolanti, la fornitura di strutture sanitarie e igieniche e il coinvolgimento della comunità locale nella vita della scuola. Un altro obiettivo importante era la progettazione di spazi adatti al clima tropicale locale, con un impatto ambientale minimo. A tal fine, il progetto si basa su materiali naturali e di riuso e segue strategie bioclimatiche. Il concetto chiave si ispira alla struttura tipica dei villaggi della Casamance, introducendo unità multiple che convergono in spazi esterni multifunzionali.

La ricerca sui bio-mattoni è stata condotta attraverso una revisione della letteratura e test sperimentali. Sono stati testati tre diversi tipi di fibre vegetali: bambù, paglia e fibre di legno. I campioni di prova sono stati prodotti utilizzando presse manuali nel laboratorio di materiali strutturali del Politecnico di Milano a Lecco. I blocchi di terra compressa sono stati poi sottoposti a prove di erosione e compressione in laboratorio. Per determinare l’impatto ambientale dei bio-mattoni è stata effettuata una valutazione comparativa del ciclo di vita sia per gli edifici che per gli elementi strutturali.

Lo studio ha rivelato che i bio-mattoni in terra cruda costituiscono un materiale strutturale a basse emissioni rispetto ad altre opzioni portanti diffuse. In particolare, l’uso di fibre di bambù ha permesso di ottenere le migliori prestazioni meccaniche e ambientali. In definitiva, questo progetto dimostra, attraverso un caso di studio, che i bio-mattoni in terra cruda possono essere una componente della progettazione di edifici sostenibili di alta qualità.

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1. SENEGAL

1.a. Geography

The country of Senegal is located on the west African coast, below the Saharan region. The surface of the country is 196,712 km² [1] and has an important maritime façade with 531 km of cost line. [2] The country is bordered by the Atlantic Ocean to the west, Guinea-Bissau to the southwest, Guinea to the southeast, Mali to the east and Mauritania to the north. The Gambia forms an enclave in Senegal, penetrating more than 302 km into the country. The capital city of Senegal is the city of Dakar, located in the extreme west of the Cape Verde peninsula, on the Atlantic Ocean. The city covers an area of 83 km² and the region of Dakar 547 km² .[3]

Fig. 1.1 - African continent and its flag @Larousse

Fig. 1.2 - Senegal and its neighbouring countries

Fig. 1.3 - Dakar aerial view @Derejeb

Senegal has a population of 18,2 million people in 2023 and a density of 93 inhabitants per km in 2023. [1] However, the human repartition all over Senegal is very inequal between cities and rural villages. People are mainly concentrated in big cities along the coast. Around 50% of the population lives in rural area. The most densely populated region is those of Dakar, the capital city, which concentrates ¼ of the total population with more than 4 millions of inhabitants in only 0.28% of the territory.

Senegal only has few rivers and most of them have their source in Guinea. This is the case of the Senegal River which defines the northern border of the country before flowing into the Atlantic Ocean at Saint Louis. It has several tributaries, including two main ones in Senegal: Faleme and Ferlo which flows are very irregular and depend on the monsoons. Similarly, the Gambia River has its source in Guinea and flows through the south-east of the country before crossing the Gambia. The exception is the Casamance River, which flows through the region of the same name, in the south of the Gambia. It is sourced in the vicinity of Kolda and irrigates the entire Casamance region.

Senegal has many saltwater and freshwater lakes. The largest lake in the country is Lake

Fig. 1.4 - Lake Guiers @EBA Senegal

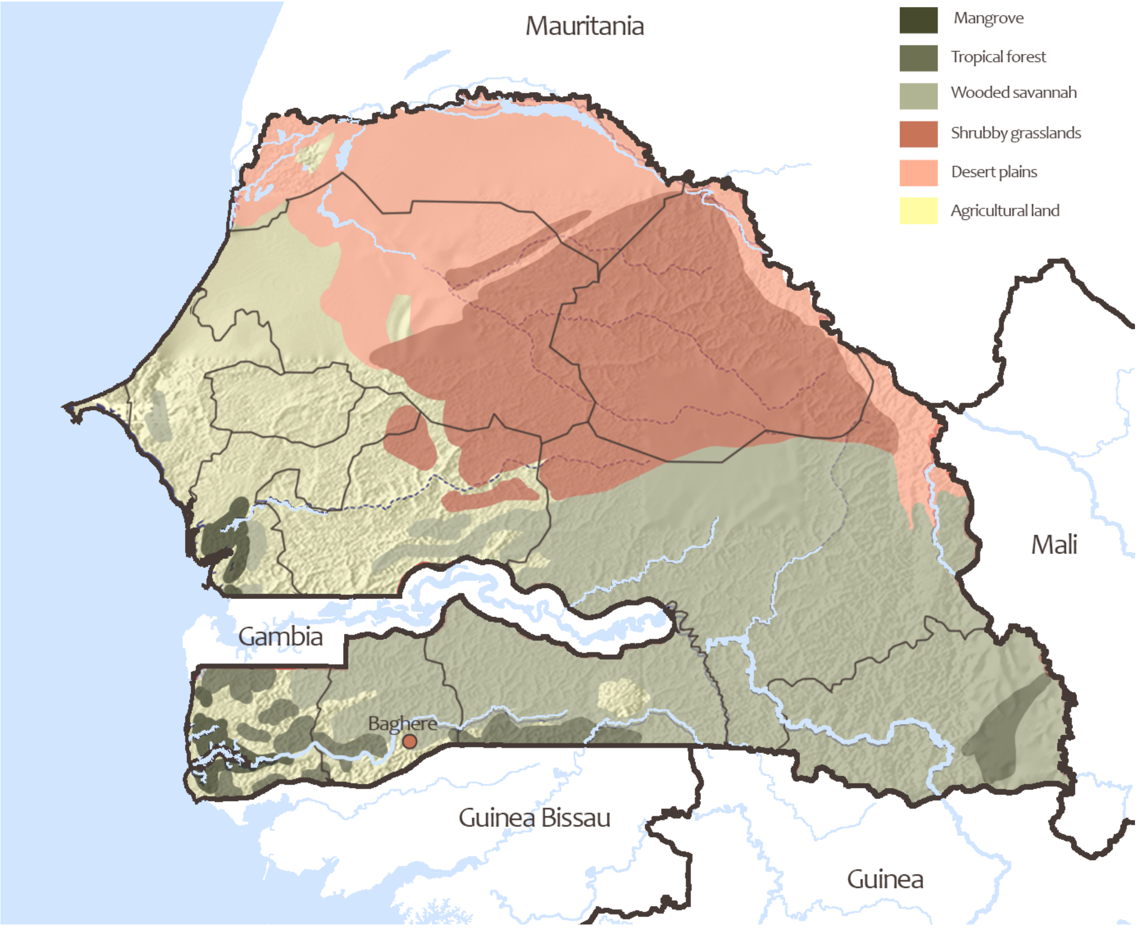


Fig. 1.5 - Map of the repartition of the vegetation in Senegal

Guiers, a 200 km² freshwater lake fed by the Senegal River in the north of the country, which supplies the capital with fresh water. The country also has many smaller lakes which sometimes constitute the local freshwater reserves.[4]

One of Senegal's assets is the number of different ecosystems. The terrain is relatively flat, except for the south-east of the country, on the border with Guinea, where the Fouta-Djalon mountains are located. They are home to numerous water streams and lush vegetation.

Regarding vegetation, Senegal has a large variety of ecosystems depending on the region. On the sSuth border with Guinea-Bissau, dense forest ecosystems are found, and in the south-west, it is mixed with mangroves, with their specific fauna and flora. Some mangroves are observed also in north of the Gambia, along the sea.

Then, the savannah is the most important ecosystem in the eastern part of the country. It is more densely wooded in the south and becomes more and more desert-like towards the north of the country, giving way to shrubby grasslands and eventually desert plains. Finally, the western part of the country above Gambia is mostly occupied by agricultural fields. [5]

Fig. 1.6 - Somone Lagoon @O.Kohler

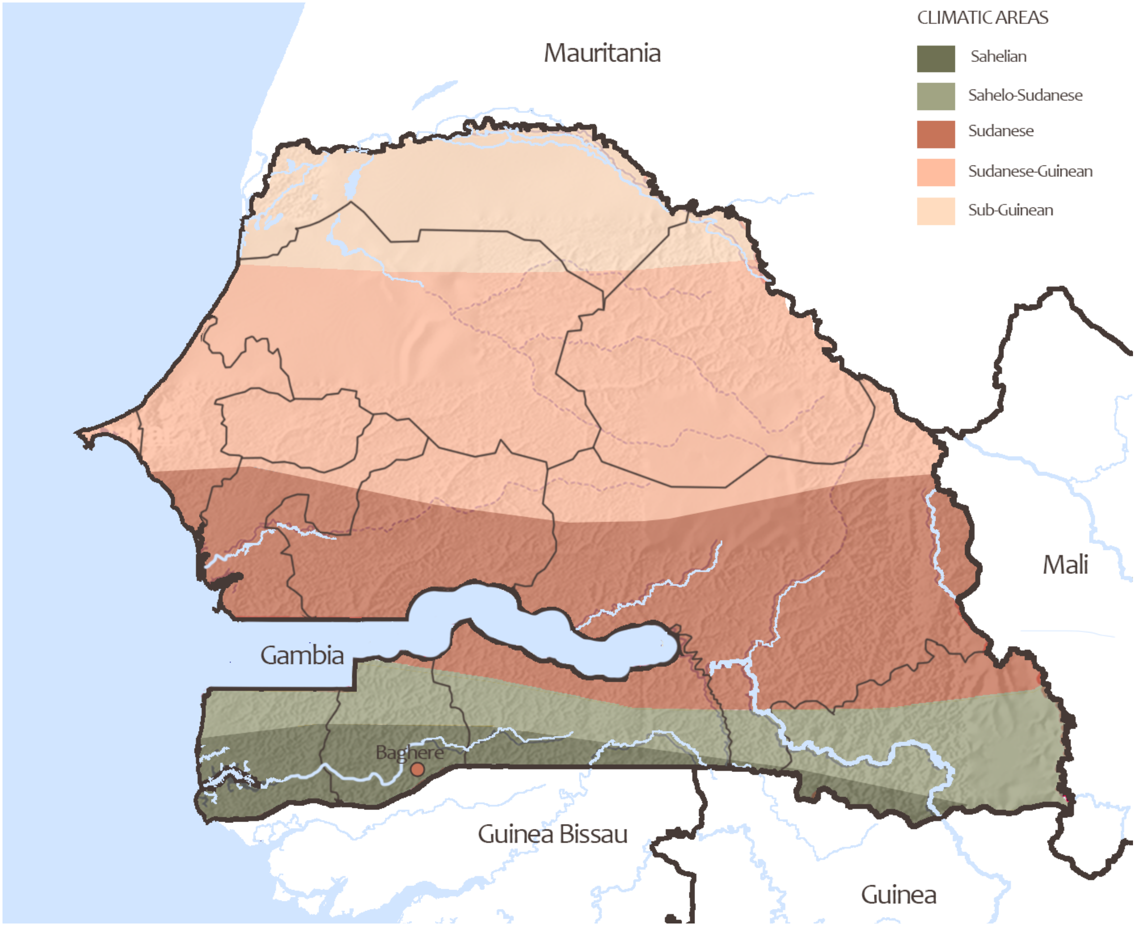


Fig. 1.7 - Climatic areas in Senegal

1.b. Climate

Located in the intertropical zone, this country is very hot and presents only a few very tropical and humid months. In general, there are two seasons:

- A dry season from November to May, with continental trade winds and mild temperatures

- A wet season from June to October also called «wintering», with high temperatures and monsoon rain.

The climate in Senegal is very diversified regarding the different regions. Indeed, from North to South it goes from a desert climate to a tropical one and the temperature can vary up to 10 degrees between the West coast and the East side of the country. From North to South, there are five main zones of tropical climate variation:

- The Sahelian zone (between Rosso and Matam / Louga) : an increasing desertification and arid climate with a temperature of 14°C in January and reaching higher temperature around 40°C in summer and average rainfall around 360 mm. [4]

- The Sahelo-Sudanese zone (from Matam/ Louga to Fatick): a dry savannah with temperature varying a lot between West and East, from maximums of 28.9 °C in Dakar but reaching up to 38.4°C in Matam. The average rainfall is 464 mm per year.

- The Sudanian zone (from Fatick to Upper Casamance): a denser savannah. In the Kaolack-Tambacounda vicinity, rainfall averages between 610 mm and 900 mm, occurring on about 60 days between June and October which makes cultivation without irrigation possible in this area. The temperature is reaching up to 36°C in summer.

- The Sudano-Guinean zone (from Upper Casamance to Kolda). In the southern Casamance area rainfall averages around 1200 mm falling on 90 days of the year and the temperatures goes from 22.5°C to 36.6°C.

- The Guinean zone (southern Casamance): mainly tropical rainforest with a tropical climate. It is in this part of Senegal that it rains the most with up to 1340 mm of precipitation and temperature going from 21.4°C to 36 °C. [6]

Finally, as far as climate change is concerned, the current climatic shocks accentuate the vulnerability of the populations, especially those in the North, where the climate is the hottest and the driest. Indeed, they are the most exposed because they are at the heart of the Sahel strip. In addition to the northern departments, some departments in the East and South also show recurrent vulnerability such as: Bambey, Gossas, Koungheul, Salémata, Medina Yoro Foulah, Linguère, Kanel, Matam, Ranérou, Podor and Sédhiou. [7]

1.c. History

Before the Xth century, the area of the actual Senegal was part of the Tekrur kingdom and was under the influence of the kingdom of Ghana. Around the XIth century, Islamization started spreading through the country imported by the Zenaga Berbers from Mauritania. Around 1040, these created a "ribat" which is a fortified religious centre. Founded by the legendary king Njajan Njay, the Wolof or Jolof kingdom was consolidated in the northern part of Senegal between the XIth and XIVth century. [8]

In the XIII - XIV th century, the Mali empire invaded the southern part of the territory of the actual Senegal. It was a Mandinka speaking regime, that expanded across the whole sub-Saharan region. The northern-western part of the actual Senegal became the Wolof empire in the second part of the XIIIth century. The Wolof empire collapsed in the 16th century followed by the Mali empire at the beginning of the XVIIth century, leaving behind small independent regions of diverse ethnicities and languages.

The first European settlements in the area were reported in the XVIIth century. They were used as slave departure ports towards America. The French were positioned in the coast of Senegal by 1659 and first founded Saint-Louis. In the XVII and XVIIIth centuries, the British and the French fought over territory, but France took the lead. The largest cities of Senegal: Saint Louis, Goree, Dakar and Rufisque were originally four colonial cities founded by the French and are thus named the «Quatre communes». In the early XIXth, and with the new interdiction of slave trade, France decides to make Senegal a colony. Different statuses were instated, creating a stark contrast between the condition of city dwellers and that of the rural population. The colonisers used collective sanctions, deportation, and physical violence for non-compliance with hygiene or urbanisation rules but mainly for political reasons. [9]

After a gradual emancipation from French governance, the independence of Senegal was proclaimed in 1960 with President Senghor from the socialist party as leader. The elections were opened to opponents in 1975. Since then, the regime of Senegal is democratic and is one of the few stable democracies in Africa. The official language remains French. The main political parties are Alliance for the Republic (APR) and Senegalese Democratic Party (PDS), whose orientations are both central liberalists. The country concentrates diverse ethnic groups that coexists in different proportions depending on the area. The main ethnic groups are the Wolofs, the Tukulor, the Serer, the Mandingo/Malinka and the Diola/Jola. [4]

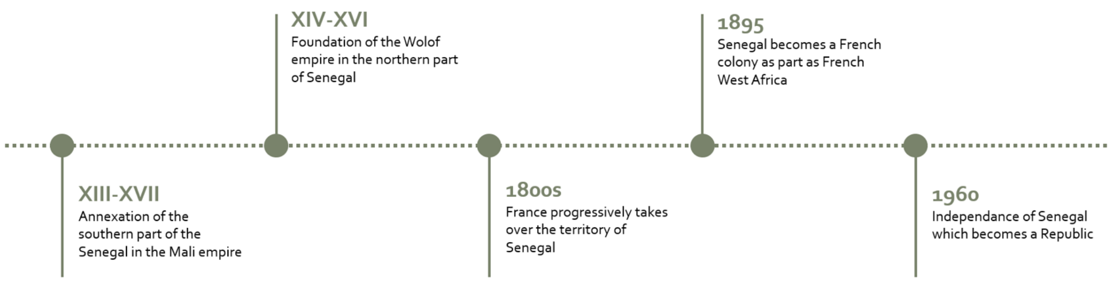


Fig. 1.8 - History timeline of Senegal

1.d. Economy

Due to its privileged geographical location and its long-standing climate of political and social stability, Senegal has been able to integrate the business world and establish itself as one of the most successful economies in sub-Saharan Africa. Indeed, the country has many advantages such as its interesting tax system, its ease of doing business, its investment protection, and its infrastructures and services, making it a safe destination for investments. All these assets make Senegal's economy 103rd country in the 2023 world GDP rank Index and the 13th out of 47 countries in the Sub-Saharan Africa region according to the Heritage Foundation. [10]

Furthermore, Senegal is an important member of various economic organisations, making it an important economic player with access to a large market of 300 million consumers. The country is a member of West African States Economic Community (CEDEAO) (15 African countries) and the West African Monetary Union (UUEMOA) (8 African countries). The mission of both organisations is to promote economic integration in the sectors of energy, transport, industry, agriculture, natural resources and trade, while strengthening the competitiveness of their economies. [11]

Since 2014, the Senegalese economy has shown sustained annual growth of over 6%. [12] Its nominal GDP in 2022 projected at 27,68 billions of dollars or 16 917 billion of CFAF according to World Bank national accounts data, and OECD National Accounts data file, making it a lower middle-income country. [13]

Besides, the implementation of major reform programmes predicts a more competitive economy in various sectors. Conducted in partnership with the World Bank, the Senegalese government under the leadership of President Macky Salls, implements the Emerging Senegal Plan (ESP), a reference document for economic and social development policies. By now, the plan is working very well in the country and has significantly accelerated the economic growth.

The economy of Senegal mostly relies on its three sectors. The sector with the largest share of GDP is the tertiary sector which represents 49.9% of GDP and 57% of employment. Besides, beyond the sanitary crisis that really impacted this sector, the tourism activity is growing a lot, creating new opportunity for jobs and infrastructures. The secondary sector represents 23,2% of GDP and 13% of employment. It is mainly based on food production , sea food processing, chemical mainly fertilizer and phosphoric acid production, and textiles. Senegalese industries also manufacture building materials, machinery, equipment, and electricity. Recently, the pharmacopoeia is being developed owing to the development of a biomedical and pharmacopeia industry park also supported by the government.

Finally, the primary sector still represents an important part in Senegal economy. Indeed, it contributes to 16% of GDP according to the world bank and represents 30% of the employment. However, the agriculture is very submitted to climate changes issues and stock exchange fluctuations.

Regarding minerals resources, Senegal is one of the world's leading producers of phosphate and has significant deposits of zirconium, titanium, marble, gold and limestone. Moreover, by 2023, Senegal is expected to become an oil and gas producer. [14]

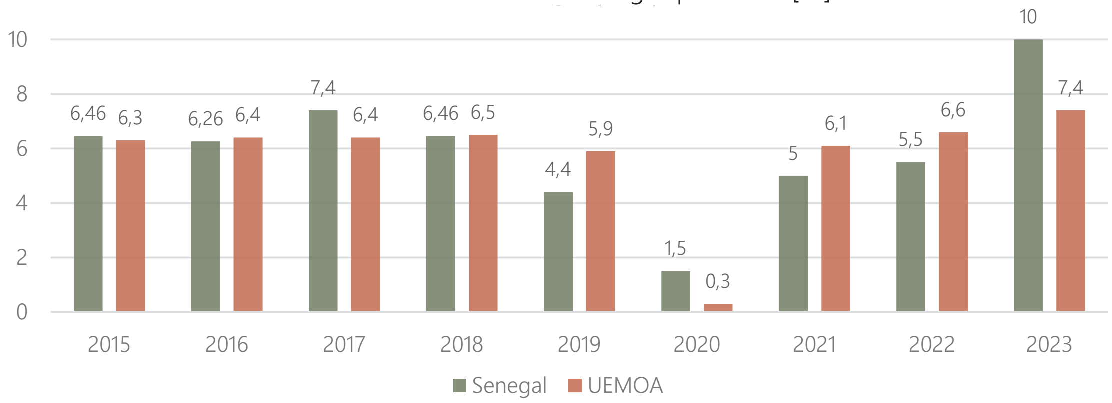


Fig. 1.9 - Comparative growth rate between Senegal and the UEMOA @Ministère de l'Economie des Finances et de la Souveraineté Industrielle et Numérique

1.e. Social analysis

The Senegal has a population of 17 million inhabitants, which is increasing with a natality rate of 35% for a mortality rate of 7%. The population is therefore really young, with an average age of 19. However, we can see that the increase in the population is slowing every year. [1]

The general health in Senegal could still be improved. Indeed, the average life expectancy in Senegal is around 65 years. On this topic, the difference between urban and rural areas is stark as the life expectancy varies from 55 to 70 depending on the regions. Moreover, the percentage of child mortality before the age of 1 is of 4% in urban regions and 6% in rural regions. For early childhood, the rate of children death before 5 years of age doubles in rural regions. Both natality and mortality rates are higher in rural regions showing great contrast in access to healthcare between richer and poorer populations.

The unemployment rate is of 18% among men and 40% among women. Among the working population, 30% of people work in agriculture and most people have low income. In fact, 47% of people live in poverty, and this number rises to 66% in rural areas, with 40% of the population living on less than 2$ a day.

The way of living also differs in different regions. Almost half of the population lives in cities. The rate of polygamous households is rather high, especially in rural areas where it is the way of living of almost 50% of the population. The average household is made of 8 people. In fact, most people live in extended households, which is the tradition for a lot of ethnic groups.

Most people live in huts or shacks, and houses are mainly auto constructed. The home equipment varies a lot depending on the region and culture. 80% of people now use electricity for their lighting device in urban areas, against only 25% in rural regions. For cooking, gas is predominant in cities, whereas wood is widely used in the countryside. Only 37% of people have running water in their house, other people either have a tap outside their home or use public fountains or wells. Only 15% of people have toilets connected to the sewers, and this number decreases even more in rural regions. Waste mostly goes into uncontrolled landfills especially in rural areas.

In short, the situation of people living in Senegal varies a lot depending on the areas and type of settlements. This idea is sometimes described as "2 Senegals" with Dakar and the major cities representing the more developed part of the country, while the rest of Senegal is much poorer and underequipped. [14]

Fig. 1.10 - Dakar street @S. Modak for The New York Times

2. CASAMANCE, SEDHIOU

2.a. Geography

Fig. 1.11 - Casamance region

Casamance is located in the South of Senegal and thus at the south of Gambia. Its surface is 28 350 km² or 1/7 of Senegal area. The Casamance river, from which it received its name, flows through the whole region on 300 km. [15] The low declivity of the riverbed makes it an arm of the sea at high tide, and creates meanders called marigots or bolongs. The river also has some tributaries that irrigates the whole region. The irrigation provided give birth to a luxurious vegetation.

Along the coast, the region contains mangroves and swamps. In the south, along the border with Guinea Bissau, the vegetation is dense and hosts tropical fauna and flora. The rest of the region is either covered in agricultural fields or wooded savannah.

The Casamance region has a population of 2.3 million inhabitants, divided into three administrated regions from West to East: Ziguinchor, Sedhiou and Kolda. Zinguinchor is the coastal region with a superficy of 7352 km² and hosts 754 000 inhabitants. [1] Apart from agriculture, this region also relies on tourism. Kolda, the eastmost region, is the most populated region out of the three with 903 000 inhabitants on 13 770 km². This region hosts the source of the Casamance river. [1]

The Sedhiou region is located between the Gambia, Guinea Bissau, Zinguinchor and Kolda. It is also called the Middle Casamance due to its position. It is one of the least developed areas of Senegal, with a poverty rate of 65.6% in 2019. It covers an area of 7 330 km², or 3.7% of the national territory. [17] 634 177 people live in the region with a density of 62 inhabitants per km². [1]

This region is later divided in three departments from North to South: Bounkiling, Sédhiou and Goudomp. The area chosen for our project is in Goudomp, the southernmost department of Sedhiou, delimitated at north by the Casamance river. There are 300 villages in Goudomp. In the department, the terrain is flat, punctuated by low-lying areas and tributaries of the Casamance River.

There are many different types of soil in Casamance which allow different uses especially in agriculture. The sandy soils and the sandy clay also known as "Bancoufing" are suitable for groundnuts crop. The alluvial clay-humus soils along the river, are the richest in organic matter. After desalination, they are used exclusively for growing rice. The others soils are ferruginous and ferralitic, with variations depending on bioclimatic conditions, and are known as «Decks». They are suitable for growing cereals and groundnuts. Clay-limestone soils are found mainly on the slopes of valleys and are suitable for growing tree and vegetables. [17]

Fig. 1.12 - Sedhiou department

2.b. Climate

The lack of an equipped weather station in the Sedhiou region makes it difficult to gather accurate numerical data. As the Sedhiou station only collects rainfall data, we will rely on data from stations in Kolda and Ziguinchor, the neighbouring regions. The year is divided into rainy and dry seasons. Within Casamance, the climate is very different from one place to another. Sedhiou has an intermediate climate between Ziguinchor and Kolda. The temperature vary from 14°C to 36°C. Rain falls on average 76 days in a year with a maximum precipitation in August of 16 mm a day. [19]

The presence of the river and multiple ponds is an asset for agriculture. The vegetation is diverse and lush, even though agricultural expansion and wildfires are threatening the natural ecosystem. [5]

2.c. History

Since the 1980's, the region of Casamance has been in conflict with the Senegalese government. Indeed, in addition to being geographically remote, the population of the Casamance region belongs to different ethnic groups than the rest of Senegal. While the largest ethnic group in Senegal is the Wolof people, which represents more than 50% of the population, they represent only 5% of the population of Casamance, where the majority is Diola. This contributes to explaining why, since independence in 1960, the people of Casamance had wanted to break away from the country. President Senghor gave them hope for a separation a few years after decolonisation, but never made it a reality. In 1982, a peaceful march in Ziguinchor turned into a bloodbath and gave way to armed conflict for independence. Until 1990, the government hunted down rebels, sometimes banning Diola cultural gatherings. Between 1990 and 2001, several ceasefires were signed but the conflicts continued. In 2001, the president signed a peace treaty with different separatist leaders, that has diminished the attacks. The army is still very present in the region and although the situation is calmer, attacks on civilians still take place, as well as trafficking in goods.

In addition to the Diola, the main ethnic groups represented in Casamance are the Balantes, the Mandinkas and the Peuls. In the central region of Sedhiou, the repartition is a bit different, for the Mandinkas are the main ethnic group, followed by Balantes and Peuls. In this region, Diolas are not as represented and it is therefore less impacted by the independence conflicts. [19]

Sedhiou, the capital of the central region of Casamance is historically an important city for the Mandinka culture. The city of Sedhiou was also the capital of the Casamance region until the XXth century when the function was transferred to Ziguinchor. The Mandinka people are primarily farmers, but some are also craftsmen (woodcarving, leather and metal working, weaving and dyeing). They live in a caste-divided patrilinear society. Traditionally, Mandinka people were divided in three castes: the slaves, the caste-members (bards, blacksmiths, leatherworkers, and Islamic poets) and the nobility. Although slavery has been abolished in the late 1800s, the Mandinka society is still subtly divided into these three categories, and one cannot easily marry someone from another caste. Every family is led by the oldest male descendant, and the village is under the authority of the male leader of the oldest settlement. The Mandinka also have an important culture of storytelling through music and poetry, illustrated by the role of the griots: musician and singers that transmit the history of the community through generations. [20]

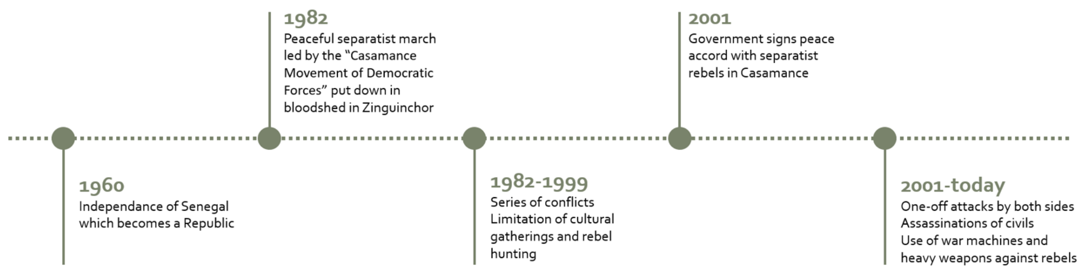


Fig. 1.13 - History timeline of Casamance

The Balantes are the main ethnic group of the Gambia. They are therefore mostly found near the border with this country. They are mainly rice farmers and cow breeders. In Gambia, they still practice their traditional animalist religion, but most of Balantes found in Senegal believe in Islam.

The Peuls were initially cow breeders. Therefore, they used to be nomad people, guiding their flock in different regions according to the season. They also have a culture of oral tradition and tell stories through songs, mostly expressed by women. They are known as warm and welcoming people, and as nomad people they are used to doing trades with the local ethnic groups.

The Diolas were traditionally cultivators of rice, fishermen and makers of palm wine. They were known as skilled builders and used to build some impressive settlements such as the impluvium houses. [4]

2.d. Economy

Sedhiou region's economy is mainly based on agriculture. Indeed, according to RGPHAE (censement Général de la Population et de l'Habitat, de l'Agriculture et de l'Elevage) [21], more than 4 out of 5 persons in the region work in agriculture which represents more than 80% of the economically active population and provides the foundations for the local industry. Indeed, due to good rainfall, fertile soils and a favourable climate, there were more than 208,050 hectares of arable land in 2019. These last years, the agricultural sector has been able to develop owing to programmes launched by the state to develop rural economy. (Donation of fertilisers, agricultural equipment, etc.)

The most important crop has been the peanut that represents around 22% of agricultural area in the region. However, since the 1980s, agriculture has been diversifying. Large surfaces are used to cultivate various type of cereals but also millet, sorghum, and plants from the Pennisetum genus of old-world grasses, grown for fodder. Rice is one of the most cultivated crops in Casamance. Its cultivation is mainly restricted to the lower part of Casamance valley and the lower part of Senegal River valley, especially Sedhiou region where small tributaries of the Casamance River and their relatively steep slope, the flooded lowlands offer possibilities for agricultural development. Indeed, according to 2022 economic report of the Forecasting and Economic Studies Department, the region produced around 357 034 tonnes of rice during the 2022-2023 agricultural season making Sédhiou region the Senegal's leading rice producer, ahead of the Kolda and Saint-Louis regions. [22] Others crops such as corn (maize), cassava (manioc), beans, and sweet potatoes are grown in significant quantities.

Fig. 1.14 - Rice harvest in Sedhiou @Afrikemergence

Besides, the ideal climatic conditions of the region, its vegetation and the rivers are very favourable to breeding. The Casamance is used for watering for the cattle, especially as the water table is tapped at a depth of 3 to 8 metres). The main species reared are N'dama cattle and some mixed breeds from local and exotic breeds.

Moreover, fish farming is also highly developed. The main species caught are carp, mullet and crustaceans and in 2019 3 655 tonnes were recovered with a market value of over 5 billion. About half of this is dedicated to local consumption.

However, the primary sector faces very critical constraints in the region. Fish farming activity is currently suffering from an increasing scarcity of fish resources and the agriculture suffers of the low level of development of areas to produce, preserve and process products, the isolation of some production areas and the salinisation of land.

Regarding the secondary and tertiary sectors, they are not as developed as in big cities. Indeed, as far as trade is concerned, there are only a few establishments in the region. 27.3% of which are specialised in trade (vehicles, fuel, etc.), followed by construction and NGO development sector for local communities. Besides, even though the region presents lots of cultural and natural assets, it is still struggling with the development of tourism. This is emphasized by the very few numbers of infrastructures in the region: only 9 hotels in the whole region. [23]

2.e. Social analysis

The region of Sedhiou has 400 000 inhabitants and is the least densely populated regions of Senegal. The natality rate is of 44%, which is significantly higher than the average of Senegal (37%) and is responsible of an increase in the population. The population of Sedhiou is young with an average age of 21 and a median at 16. The central department of Goudomp is the most populated of the three that compose the region. It is one of the least developed regions in the country, with an average urbanization rate of 15%.

Different ethnic groups coexist in the region, Mandinkas, Mancagnes, Manjaques, Balantes, Peuls, Diolas, Wolofs and Bambaras. The Mandinka are an ethnic group coming from the region of Mali, which speaks Mandinka, they are the majority in the region. The Peuls and Wolofs are two important ethnics groups in Senegal and both have their own language. The Mancagnes, Manjaques and Balantes are mainly present in Guinea Bissau but also in the south of Senegal, and they each speak their own language.

Islam is the religion of 95% of the population. In Sedhiou, polygamy is among the highest of the country, with a 48% rate of the population. The average household contains 11 people, because they are usually composed of extended families. 70% of people live in huts or shacks, and almost every home is self-constructed.

More than 4/5 of households in Sedhiou practice agriculture and around 90% live in poverty. The region also suffers from a lack of infrastructure, that makes the access to telecommunication and electricity underdeveloped and uncertain.

The unreliability of the electricity and water networks can be illustrated by the way of living of people in Sedhiou: the lighting devices most used are rechargeable lamps, electricity powered lamps, candles, and storm lights. For cooking, 90% of people use woodfires. Most people have open toilets, not connected to an evacuation system, followed by covered toilets, and 11% of people simply don't have sanitary facility and go in the wild. 72% of households evacuate their waste in illegal landfills, 10% into legal landfills, and the rest is incinerated. Around 80% of people drink water from sources that are not safe.

For all these reasons, the general health of the population is rather concerning. The life expectancy is of 57 years in Sedhiou, compared to 65 on average in the country. Most adults have no medical coverage. In Sedhiou, child mortality is among the highest of Senegal with 12% of children dying before the age of 5. [23]

Fig. 1.15 - Sedhiou street @Wordpress

Fig. 1.16 - Access to drinking water in Sédhiou @P. FAYE

2.f. Accessibility

The road network of Sedhiou region was 1628 km long in 2019. National and regional roads are under the responsibility of the state while departmental and rural roads fall under the exclusive jurisdiction of the local authorities. Roads under the responsibility of the state are often made of hard materials (macadam, tar, asphalt...), making them more durable. For example, started in 2017, Eiffage Sénégal carrying out the construction of different regional axes on the Boudier loop :

- The Sedhiou / Kamoya / Marssaoum road of 54 km long
- The Sedhiou / Bambali / Djiredji / Marsassoum road of 81 km long
- Roads in the town of Sedhiou
- Roads in the town of Marsassoum

These works were part of the priority programme to open up the natural region of Casamance. [24]

Fig. 1.17 - New regional roads in Sedhiou @Eiffage Senegal

Rural roads are often the result of the regular passage of cars. Indeed, 77,6% of the roads are unsealed roads. Thus, there are just dirt roads and sandy-clay tracks that are impassable in the rainy season. This causes a huge problem of isolation of certain villages in the region which has a real impact on the village economy and health of the population.

Moreover, other constraints need to be tackled to upgrade the accessibility issue such as the obsolescence of the vehicle fleet, the lack of vehicle regulation and the high cost of transport.

The river Casamance also represents a strong obstacle for mobility in the region, as no bridge allows its crossing. To go from the south of the river to the north, one needs to travel to Sandinier 15 km north from Baghere and take a boat from there to Sedhiou.

Indeed, being an important transit area between the different regions but also Senegal and other countries and a true treasure trove of resources (agriculture, fish, catering...) the region must present a functional road network. Thus, important projects are being established such as the Boudié networks to address this issue. [16]

Fig. 1.18 - Dirt road @P. Moctar

3. BAGHERE

In order to gather the most accurate informations on the village of Baghere we contacted Raoul Vecchio, the president of Balaou Salo association. With the help of its testimony and its experience in the village of Baghere, we were able to understand better the life of the village and its history.

3.a. Geography

The project takes place in the department of Goudomp, in the Tanaff valley. This valley is developped around a reservoir, and counts 5 cities: Baghere, Tanaff, Dioudoubou, Simbandi Brassou and Niagha.

The commune of Baghere is composed of 23 villages inhabited by a total of 15 000 people. The administrative borders of the commune are meeting the protected forest of Balmadou up north, the frontier with Guinea Bissau down south, the border of Niangha on the east, and the border of Dioudouboue and Simbandi Brassou on the west.

The north of the commune of Baghere is mainly forests, where the topography is made of tropical plateaux with cliffs. The vegetation is diverse and exuberant. The activity is mostly breeding and logging, but orchards are also developing.

The centre of the commune is in the valley, around tributaries of the Casamance river. This area is characterised by the culture of rice and palm trees. Some orchards contain mainly mango trees, cashew trees and citrus trees. The area is also characterized by some low-lying floodplains where the groundwater can be easily accessed at 3 to 8 meters below the surface. This central area concentrates the largest part of the population and the most infrastructures among which the city of Baghere with 2500 inhabitants.

On the south, at the frontier with Guinea Bissau, there is a sparse forest. This area contains many orchards around the villages and is also partially covered in fields replacing progressively the fallows and forest. Indeed, the forests are diminishing due to the exploitation of the resource and the frequent wildfires. Breeding in the area is decreasing. [25]

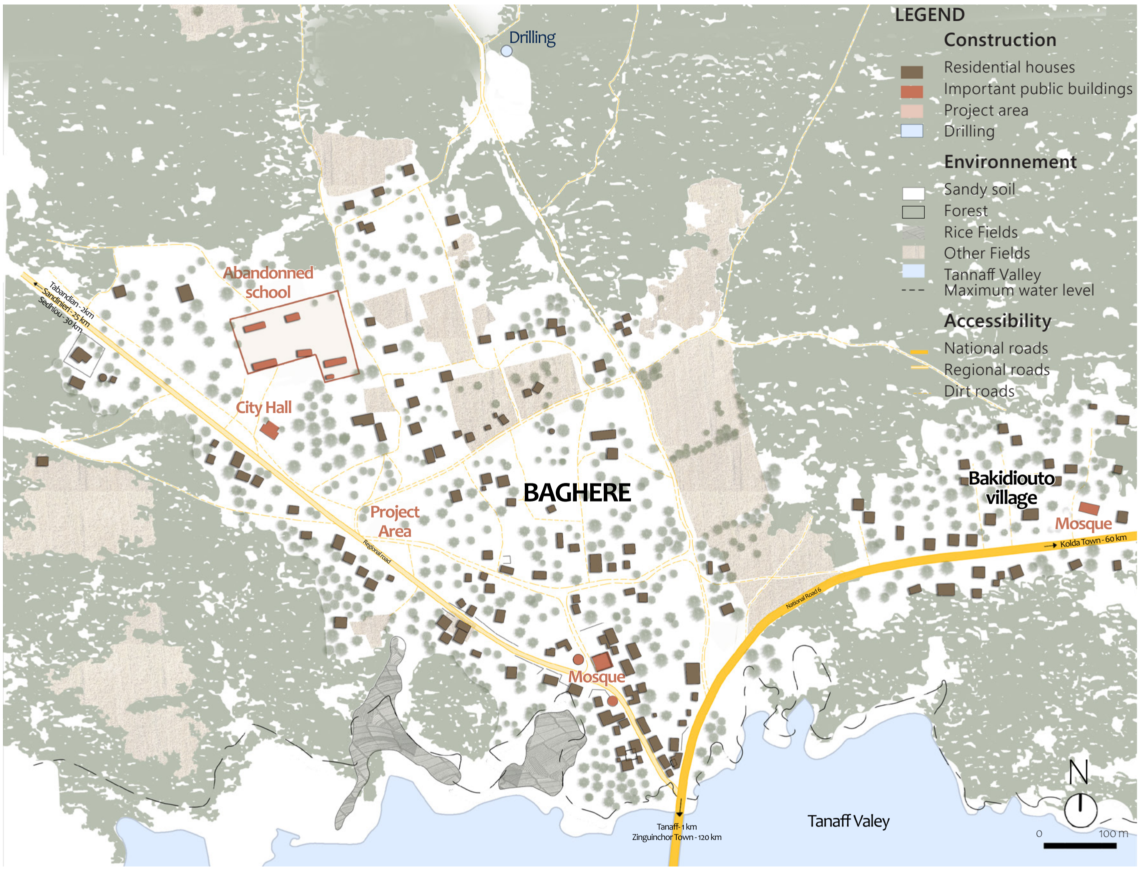


Fig. 1.19 - Map of Baghere

Regarding the fauna and the flora, there are various animals in Sedhiou region. As there are both dense green forests and savannah, there is a great diversity of species. This includes hares as well as monkeys, birds such as the crop-destroying red-billed quelea, partridge and guinea fowl.

3.b. Climate

The village of Baghere is located in the Sudano-Guinean zone and contains both savannahs and dense forests. This area is generally hot, humid, and uncomfortable.

- **Temperature**

The temperature varies from 15°C in December to 45° in April or May. The average temperature is between 25 and 32°C all year long.

- **Relative humidity**

The air is especially humid during the rain season from July to November with a maximum relative humidity of 95%. During the dry season, the average relative humidity varies between 40% to 60% making it a comfortable climate but can still reach uncomfortable maximums of 80%.

- **Rainfall**

In Baghere there is an annual average rainfall of 1 096 mm over 74 days in the last decade. This data is characteristic of humid tropical climates, with a dry season of seven to ten months alternating with a rainy season of two to five months. Recently, the rainy season arrived late in June. Due to climate change, since 2012, the good period of June and July, is very poorly watered.

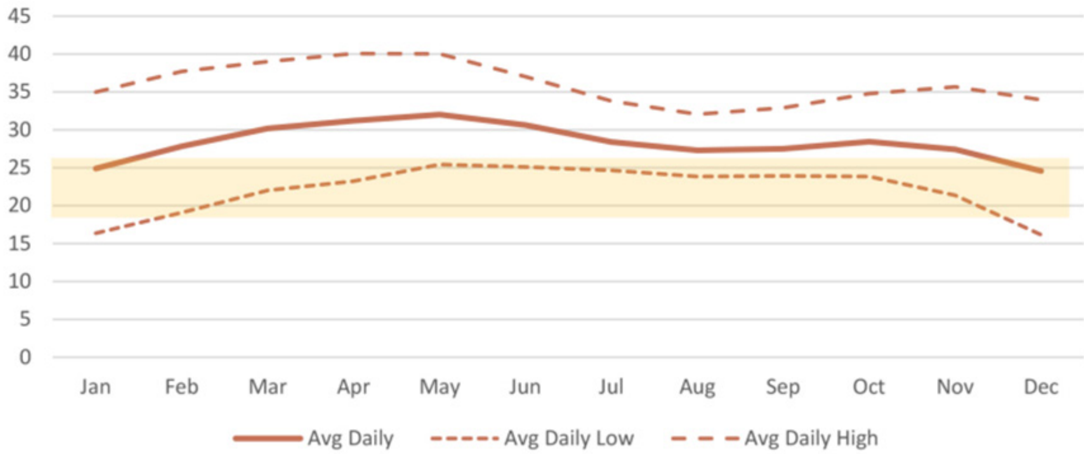


Fig. 1.20 - Average temperatures in Kolda @NOAA's

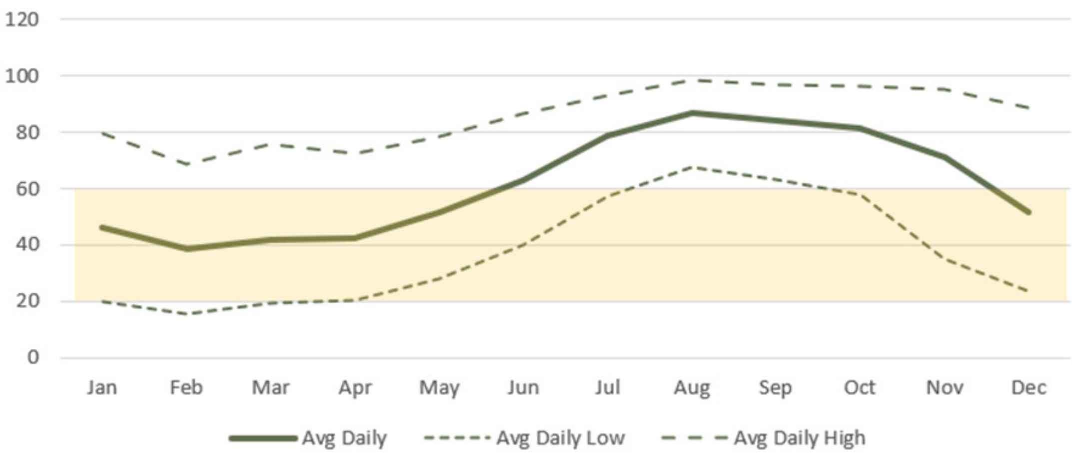


Fig. 1.21 - Relative humidity @NOAA's

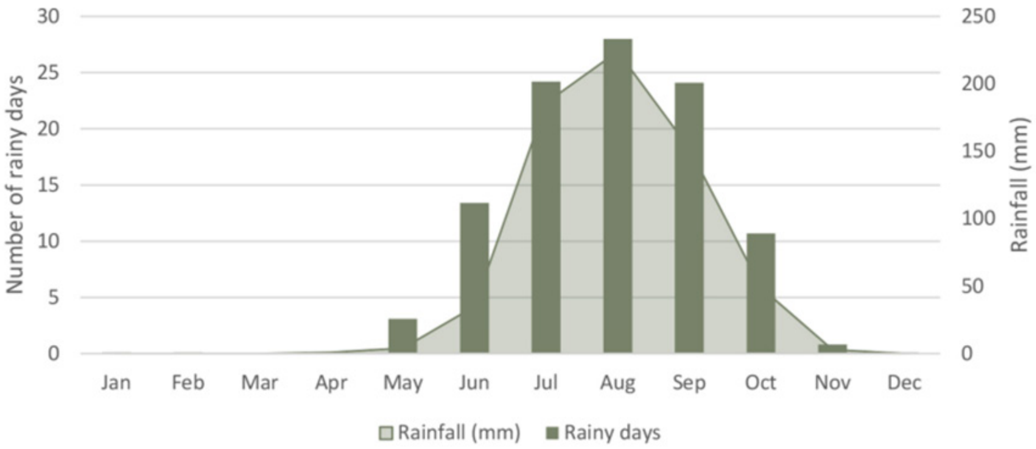


Fig. 1.22 -Average rainfall in Kolda @NOAA

- **Wind**

The winds are periodic and are of three kinds depending on the time of the year as shown in Fig. 1.24. From November to March the warm and dry harmattan blows from East to West and leaves a thin layer of sand on his path. It brings no precipitation apart from a very light rain, also named as heug by the Wolof people.

From March to May, the trade wind blows from West to East. From June to October the dry monsoon heralds the rainy season. It is a northeast trade winds and a moist rain-bearing wind blows primarily from the west. As the Inter-Tropical Convergence Zone (ITCZ, a band of clouds consisting of showers, with occasional thunderstorms) returns southward at the beginning in September, the rainy season draws to a close. The slow north-south migration of the ITCZ results in a longer, heavier rainy season in the southern part of the country.

- **Solar radiation**

The sky is overcast during the rain season from July to October, diminishing the solar surface radiation, while it is clear during the rest of the year. The illuminance is still rather high all year long, with the average surface radiation varying from 300 to 600 Wh/m^2, which corresponds to approximately 1,6 times the radiation in Milan.

In addition, the climate evolves rapidly. The rain season is progressively becoming shorter and more intense, causing flooding and periods of drought. At the same time, the temperatures keep rising threatening the crops and ecosystems. Indeed, between 1960 and 1990, the temperature has risen by 1,7° and the rain levels have diminished by 35%. The prediction for 2050 are even more frightening, as the warming is estimated between 1° and 3.5° whilst the rain levels could face a decrease of 60%. [26]

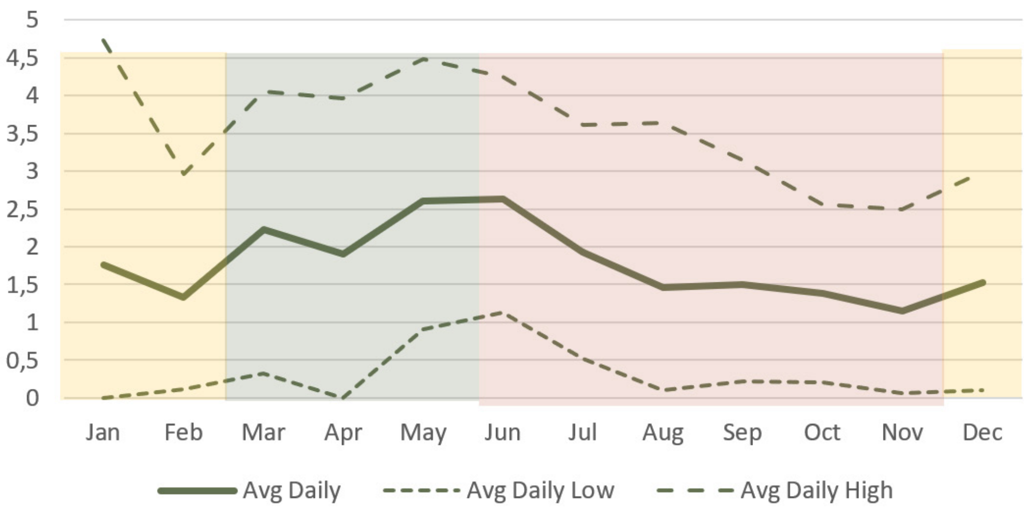


Fig. 1.23 - Average wind speed in Kolda @NOAA's

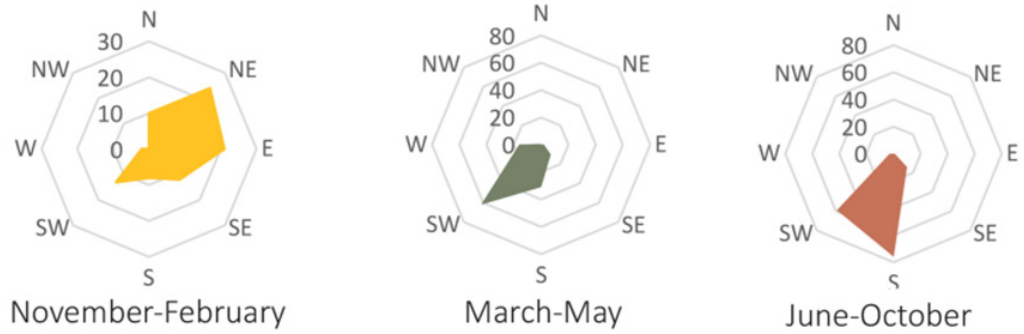


Fig. 1.24 - Average wind direction in Kolda @NOAA's

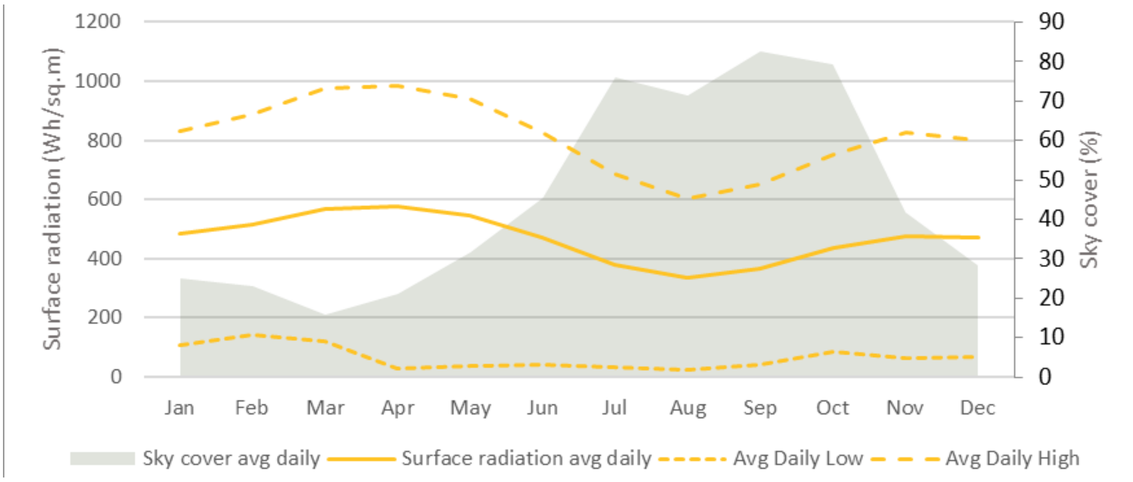
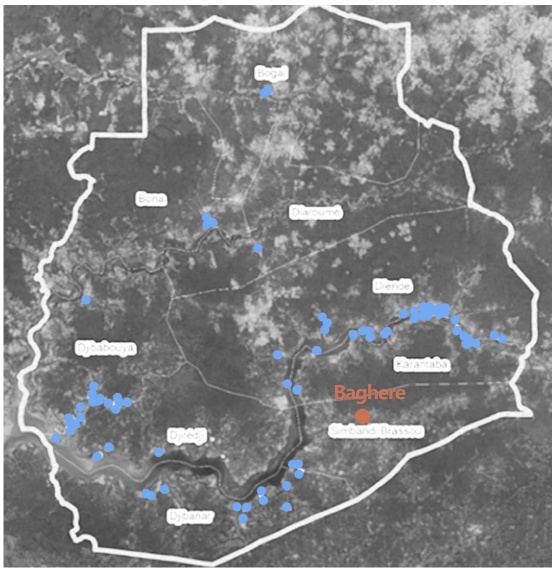


Fig. 1.25 -Surface radiation and sky cover in Kolda @NOAA's

A study by The Alliance of Bioversity International and International Center for Tropical Agriculture (CIAT) as been abled to identify the areas at risk of flooding in the region of Sedhiou illustrated by blue spots. An area was considered flood-prone if flooding occurred at least 3 times throughout the 9 years historical period considered. We can see one area at risk of flooding close to Baghere. [27]

Because of poor weather conditions observed in recent years, the standards of living of households in these places are already considerably affected: it led to poor harvest season and food crises. Climate change has dreadful consequences in this region on multiple levels. Ecosystems suffer from salinization and desertification, as well as catastrophes like flooding and wildfires. Crops are threatened by droughts, pests, and diseases. All of these hanges in agriculture and ecosystems can lead to health crises from malnutrition or viruses along with material losses due to catastrophes. [26]



LEGEND :

- Flooding area
- City of Baghere

Fig. 1.26 - Flooding area in blue @CIAT

3.c. History

Baghere was created in 1911 by Cherif Younousse Aïdar, a descendent of the prophet Mohammed. According to the legend, God would have sent him there and Cherrif Younousse Aïdar dreamt about the city that he saw in his dream next to a branch of the river. After travelling through many villages from Bambadiong to Sardiniéry to spread the muslim religion, he settled himself in Baghere. The location was chosen for both religious reasons and its interesting position regarding commercial activities.

He created the village with the help of the French settlers with whom he collaborated. Thus, he showed to its people that the settlers were not here to make their life more difficult, but could help them in their development. He had all his disciples in Casamance of which his son, Chérif Bachir Aïdara, who was the first one to say the prayer in the big Mosque of Ziguinchor, owned by the Aïdar family and in which rests the Cherif Younouss Aïdara, giving a sacred status to the building, place of prayer and pilgrimage.

Thus, in Baghere, the main religion is Islam and, due to its history, the city was one of the first place in Casamance to host a Gamou which is a large annual pilgrimage to commemorate the birth of Muhammad.

As in most of muslim villages, there is a Mosque. Every year thousands of believers and faithful come from all around the word. However, the Mosque is to be rebuilt as far as it is very damaged and new infrastructures are needed to welcome the faithful. [28]

Fig. 1.27 - Mosque of Baghere @Balouo Salo

3.d. Economy

In Baghere, as in the region of Sedhiou, the economy mainly relies on agriculture. Even though it is quite hard to have a right approximation of the cultivated areas, the crops and their production can be easily identified.

For a long time, groundnuts were the most common commercial crop in the rural community. This is due to the establishment of an agricultural programme supporting this cultivation and providing materials to the producers. However, the programme ended in 1980, leaving room to produce new crops such as rice and other cereals (maize, sorghum, sesame niebe and fonio). Other crops such as cassava, potato and «Diabéré» are grown in Baghere.

Although the land is suitable for market gardening, this area is not very well exploited. There are only a few crops of tomatoes, onions, sorrel, okra and chilli. This under-exploitation is due to a lack of equipment to produce and protect the crops, but also to difficulties in marketing the products due to market saturation and a precarious road network that encloses the area. There is the same situation with the fruits market. Indeed, even though Baghere has a large variety of fruit trees such as mango, maada and mahogany apple trees it is not exploited because of a lack of collection and processing infrastructures.

However, periodic drought at the end of the 20th century limited agricultural production. This situation is expected to worsen. Indeed, Senegal is 70th on the world index for climate risk. Agriculture and fishing are the most vulnerable sectors. Because of high temperatures, droughts will occur twice more as nowadays. Fortunately, the Manantali dam located in Mali has alleviated some of this issue by providing water for large areas of newly irrigated land. Besides, the State of Senegal had begun the construction of a borehole to supply the commune and the surrounding villages with water. To face this important drought issue, new drought-resistant strains of plants have also been developed. Another issue to take into account is that the valley is subject to desertification and salinization because of climatic changes. This phenomenon of saltwater intrusion has resulted in the loss of 10,000 hectares of arable land, as well as contamination of the soil and the wells. [25]

3.e. Social analysis

Today, almost 2,500 people live in Baghere, of which 58% are underaged. The ethnic groups represented are Mandinka, Peuls, Mandjacks and Balantes. Islam is especially important in the village, as it is a sacred place, and the islamic hierarchy plays a crucial role in every decision. In fact, the caliph has more influence on the village than the mayor. This directs certain aspect of the life on the village concerning the cultural events or the role of women. Only certain families are allowed to settle in the village. This control by the religious hierarchy has led to a greater development of Tanaff rather than Baghere.

The municipality of Baghere develops their own investment plan and development plan every 3 to 5 years, with the help of the regional agency for development (ARD). It covers the topics of health, education, water resources, sport, environment, gender equality, agriculture, breeding, trade, transport, communication and energy.

The city infrastructures include a town hall, an emergency medical service, a primary school, a mosque and an auger. All this infrastructure is globally located along the main road of the village which is connected to the national one. This road is not only a a place where people pass through, but also an important meeting place for the village. Regarding the school, it is currently in an advanced damage state making it unusable. Children are forced to go in other villages to attend class.

The activity in the village is mainly agricultural. Many people are therefore living in poverty. To trade goods, the market takes place once a week in Tanaff. There was an initiative to start a weekly market in Baghere but with no success.

The average household is composed of 17 people which represents an extended family centred around a male head of the household. Polygamy is decreasing because of economic conditions that do not allow for the maintenance of even larger families.

In the next year, the building of purification plants and an educational center are planned. The plan for investment 2021 of the commune of Baghere also mentions the construction of a new primary school and a youth center. A lot of families still do not have access to safe drinking water and 60% of the population live in houses without direct access to electricity.

Fig. 1.28 - City Hall @Balouo Salo

Fig. 1.30 - Entrance of the village @Google street view

Fig. 1.29 - Abandoned school @Balouo Salo

Fig. 1.31 - Medical center @Balouo Salo

The rate of child malnutrition is one of the highest in the country, and 1 in 3 children is at risk of malnutrition, resulting in a mortality percentage higher than the national average. If child malnutrition is so important of a topic, it is because it influences the development of the child and may lead to irreversible deficits. The causes are poverty, the environmental crisis and its impact on agriculture, contamination of the soil, and inaccessibility to medical care. But the principal factor is the contamination of the water to which around 60% of infections are due, including diarrhea, giardiasis and cholera.

Regarding water access, the current hydraulic network is composed of wells, boreholes, standpipes, ponds and marigots. The village of Baghere has a public drilling found north of the village that provides water to the entire community. This source is reliable but the distance from houses and other buildings is still limiting the hygienic conditions for the population. Regarding this issue, new projects should be concretized. The most recent of which is the construction of latrines with Idev-ic. The Balouo Salo association is also building a solar well in the village. [25]

Fig. 1.32 - Well in Baghere @Balouo Salo

Fig. 1.33 - Traditional pirogue @Balouo Salo

3.f. Accessibility

Roads that cross the village or pass by it, are shown in Fig. 1.19. The most important one is the national 6 road which serves the Community of Baghere. It is also known as the South Road, since it links Goudomp-Taanaf-Kolda, which is part of the classified network. Besides this classified network, there is a network of rural tracks linking Baghere to several other rural communities and villages in the area.

As in many other parts of Casamance, the roads are mostly dirt roads and sandy-clay tracks that are impassable in the rainy season. Thus the asphalting of the Sandinièri-Baghère axis is a priority and is being taking care by the recent report published in March 2022 by the ACE/ECIA group Environmental and social impact assessment for the Sandinieri – Tanaff – Bissau Guineas border roads. Indeed, rural roads, which are under the responsibility of the Rural Community, are in a very advanced state of deterioration. Besides, the lack of passable roads leads to the enclosure of many agricultural production areas but also of many villages, especially during the rainy season, blocking the intra-community circulation of agricultural products. This situation makes villages in the interior, such as Sansansoucouto and Kandjenou, almost inaccessible. Road construction projects should start with the founding of the African Development Bank. [16]

Other difficulties faced in this sector of accessibility to the cities are the lack of road station and the inadequacy and obsolescence of the vehicle fleet, the absence of a bus station and the inadequacy of production tracks and their poor conditions.

In Baghere, the means of transport are composed of taxi Brousse, mopeds for short journeys, shuttling between Tanaff and some other villages in the area and the ferry. The ferry makes two trips a day. It is most used by vehicles that need to cross the Casamance River to reach the rural community of Dioudoubou and Baghère and the commune of Tanaff. Otherwise, people usually use traditional pirogues to cross because it is quicker and more economical as shown in Fig. 1.33.

Fig. 1.34 - Aerial view of the village of Baghere @Balouo Salo

3.g. Energy and communication network

The energy network in Baghere rural community is still currently quite underdeveloped. Baghere is the only village with direct access to electricity with a medium voltage electricity transmission line located on both sides of the road. In developing countries such as Senegal, this situation often occurs in village where there is not production firm, and which are mainly oriented towards housing.

Currently, there are different energy resources used in villages, from most to least common: paraffin mainly used for domestic lighting, wood fuels, electricity and butane gas. Because of poverty and a high demand for wood fuels, butane gas and improved stoves are still marginally used in local household consumption. [21]

Regarding electricity, difficulties faced in this large community are various. First of all, there is an issue as far as exploiting the energy potential is concerned. Moreover, voltage often drops and power cuts. Finally, another problem to tackle is the high cost of energy. Because of difficult access to the electricity system there are less subscribers which leads to a non-profitable system and business all in all.

Regarding mining and quarrying resources, even though there are lateritic quarries, exploitation remains difficult. Because of a lack of regulation on it, the exploitation becomes a real source of numerous conflicts in the rural community. The operators of these quarries refuse to pay parking fees resulting in a huge loss of income for the rural council.

As a result, there are lots of detrimental consequences such as insecurity, darkness and the problem of preserving products. Therefore, there is a huge need for facilitating access to electricity by reducing the cost of electricity, densifying and extending the network and maybe also exploring the renewable energy track.

To face this issue the Rural Council has established different project. One which could be a great change for the village is the electrification of the villages of Djarifé, Bakidio to, Kénéwal, Kafoul, Kandjenou-Soucoutoto, Diamaye and Francounda with partners such as the Chinese Cooperation and the Regional Council (electrification of Diarifa, Kafoul, and Diamaye), the State (electrification of Bakidioto and Kénéwal) and PERACOD (electrification of Kandjenou soucoutoto, Francounda). Moreover, with ECOWAS support the Diourdioundé power plant will be implemented. [29]

The telephone network is transmitted by mobile phone operators such as Orange, Tigo and Expresso.

3.h. Topography and soil characteristics

Baghere topography is a succession of tropical ferruginous plateaus with rocky outcrops in places and dead valleys formed by the small tributaries of the Casamance River, with a relatively steep slope. Floodable lowlands give the opportunity for agricultural development and watering for cattle.

The soils are predominantly clayed-sandy on the plateaus of Deck Dior, while in the valleys, there are clay soils with a compact structure. This hydromorphic soil is very suitable to cultivate rice. However, there are differences between the zones in terms of land use, farming systems and climatic conditions.

The «Baghère» zone is an area of ferralitic soils, particularly in the south-eastern strip. This means that weather alteration had led to the creation of kaolinite, that is the main constituent of this soil with iron oxides, hydroxides and aluminium hydroxides.

Under the effect of salt, the soil in the valleys has oxidised, forming a white crust, regularly covered with reddish sand dust. In the border zone or the «Lamel» zone, the strong agricultural pressure on the plateaus has accentuated the impoverishment of the soil. Only the south-western strip on the edge of Guinea Bissau is still dominated by clay to clay-sand

The water table is located at a depth of 20 to 35 m, but in the lowlands, it is 5-7 m. Depending on the location, it is generally salinized to a greater or lesser extent depending on the area. Not only is it subjected to salinization but also desertification because of climatic changes. The rare phenomenon of saltwater intrusion has resulted in the loss of 10,000 hectares of arable land, as well as contamination of the soil and the wells. This is a serious issue as far as agriculture is concerned. Indeed, being the main economy of the region, the issue must be tackled to avoid important consequences.

The seismic analysis of Senegal has led to the conclusion that the risks of earthquakes are low in the country and particularly in the region of Sedhiou. The peak ground acceleration (PGA) that can be exceeded at maximum once in 50 years is of 0.004 g which corresponds to the Mercalli scale level IV: a light perceived shaking and no potential damage. [30]

Fig. 1.35 - Typical road in Tanaff @Balouo Salo

4. EDUCATION

4.a. History of school in Africa

- **Pre-colonization (-XXth century)**

The school buildings as they are found today in Africa were introduced by missionaries as part of the colonization process to provide western education to local children. Before the XIXth century, education had different forms. The indigenous education was more or less important depending on the ethnic tribes, and was mainly focused around initiation rituals. There was for the most part no formal teaching, and the skills were to be learnt by doing one's part of the community's labour. Rich African traders and kings would sometimes send their children in Europe to get an education. In the VIIth century, the rise of Islam in African countries brought with it madrasa schools : koranic lessons often provided in the mosques or outside.

- **Colonisation (1900's – 1960's)**

The first missionaries' schools were usually built outside of the villages because of the resistance of local people. The construction materials were prefabricated and shipped by boat for coastal settlements whereas away from the coast, the local techniques of earth and wood construction would be used. With funding from the rich colonial government, the schools were well maintained and equipped. The buildings however were not adapted to the local climate creating poor learning conditions. In the XXth century, the first studies of architectural design for tropical and desert climate were published and slowly applied to colonial schools. The school buildings became better suited to local climatic conditions but the areas covered by schools would however be inequal and insufficient.

- **Independence (1960's-1980's)**

In the 1960's the new independent government had to resort to mass schooling schemes to provide education to all the population. The funding would come from international organization such as the UNESCO, the UN or the World Bank and would therefore vary with the global economic situation. The UNESCO provided standards for school buildings in Africa, that would be massively applied with little to no consideration for the local characteristics. The typical school built between the 1960's and the 1980's was a single-storey structure composed of three to four 40 m^2 classrooms connected on one side to a covered open corridor. All the windows and doors would be bare openings towards this corridor. The building was made of locally produced cement blocks with a corrugated iron roof. In rural areas, the walls would often have no finish, the floor would be concrete screed and no ceiling was added. The sanitation facilities were dry pit latrine, found in a separated building, sometimes equipped with the Ventilated Improved Pit system introduced by the UNESCO.

- **Liberalization of education (1980's – today)**

In the 1980's, education became liberalized resulting in more inequalities between territories. On the one hand, innovative designs would emerge mainly in big cities, introducing new school design concept from European experiments. For example, the child centred learning model would aim at making the classroom more similar to the home environment, and at bringing the furniture to the child scale. The concern for sustainability also emerged in the 1990's in building design bringing concept for the reduction of energy consumption such as passive cooling and lighting or water recycling. Other functions were also progressively associated with schools, such as healthcare facilities, residential accommodation for students or community uses during out-of-school hours. More recent concepts finding their way into school design are the flexibility of spaces, and open-air classrooms. However, still today, there is a huge difference in possibilities and quality of education provided in rural and urban areas. In rural villages, many schools are still the typical UNESCO buildings, unsuited for the climate and local culture. [31]

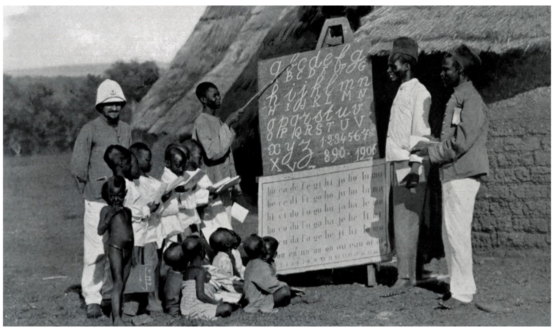


Fig. 1.36 - Children's school in West Africa @E. Fortier

4.b. Education challenges in Senegal

The Senegalese education system is composed of pre-school from ages 3 to 6, primary school from 6 to 11, middle school from 12 to 16 and high school from 17 to 19. After High School, students can attend post-graduate education in universities or professional education institutions. Education is mandatory in Senegal between the ages of 6 and 16 years old. However, the educational level in the country is rather low: around 60% of the population has an educational level of primary school or less. 25% stopped their education after middle school, and only 5% of the population has a post-graduate education. [14]

The situation is all-the-more critical as statistics show strong relationships between low education and unemployment. Education at a higher level could help people out of poverty by allowing them to find more intellectual functions. Education was also found to lead to better health and social outcomes. The age at which women have their first child is in average 2 years later for women having received secondary education. People receiving higher education also have a better probability of using contraceptives. [32] Schools can indeed also teach hygiene and sanitary habits creating better living conditions for the young people of rural settings.

Schools are sadly not accessible in the same way to every child. In sub-Saharan Africa, children living in rural areas are 23 points more likely to go out of school before the legal age. The distance to the nearest school plays a role, with an entry rate in primary school of only 41% when the school is at more than 5 km away from the household, whereas the entry rate is 73% when the school is at a distance of under 300 m. But the income of the family also has a direct impact. The gross enrolment rate of the bottom 40% income is of only 80% when the gross enrolment rate for all rural areas is of 87%. [32]

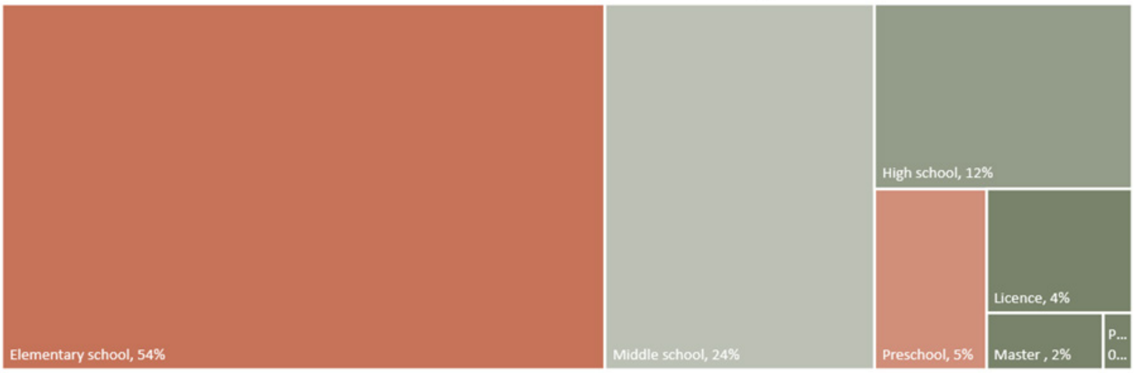


Fig. 1.37- Level of education among the population of Senegal in 2013 @ANSD

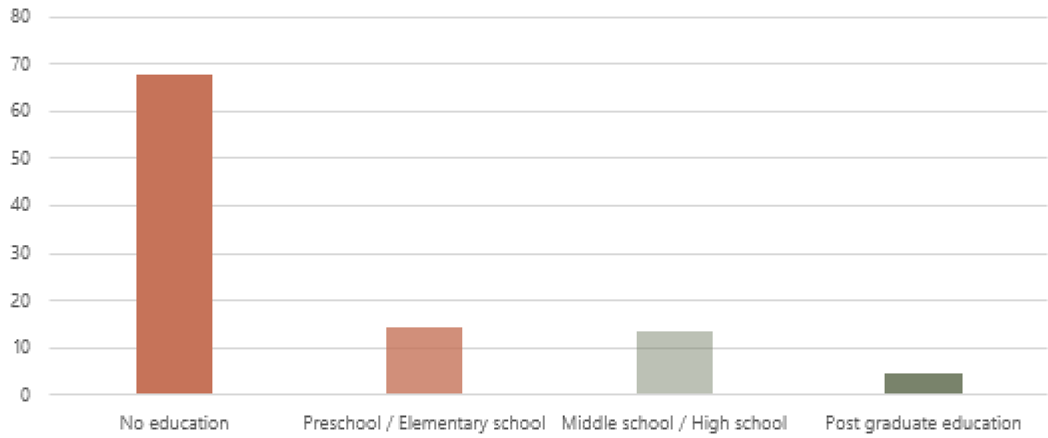


Fig. 1.38- Unemployment rate among the active population in Senegal by level of study @ANSD

4.c. Education in Sedhiou

The education rate is increasing in the region of Sedhiou and attaining the national requisites. Different indexes are used to monitor the education access:

- The gross enrolment rate: it represents the number of students enrolled in school divided by the number of children in age of being enrolled. A gross enrolment rate can be superior to 100% if some students are enrolled in these classes despite not being of the official age for this level (late access to school, repeating school years).

- The exam success rate: it represents the proportion of students that passed an exam among all the students registered.

In primary school, the gross enrolment rate of Sedhiou was of 103% in 2019. Yet the success rate for the CFEE (final exam of primary school) was only of 51%. This result illustrates the poor conditions of teaching in the region.

The first issue concerns the teaching staff. On average, every teacher in Sedhiou is responsible for 37 students: there is a shortage of teachers in the region. Moreover, many teachers are underqualified: 34% don't have the Baccalaureat (High school diploma) which is the minimum level required for teaching in primary school, and only 1% have a post-graduate diploma. At last, the teaching staff is regularly changing as more experienced teachers find opportunities in the urban areas of the country.

The quality of the lessons is also affected by the multigrades class that still represent almost 15% of all classes. The poor condition of the school buildings also affects the results, as the climate is quoted to be an obstacle for the compliance to the time quantum. The buildings are also not always well adapted to teaching and lack educational, sanitary and electrical equipment. [33]

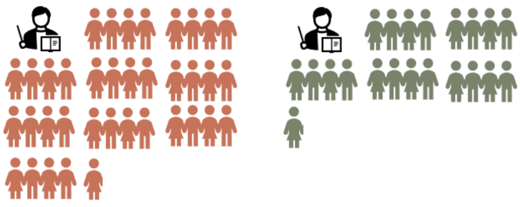


Fig. 1.40 - Number of students per teacher in primary school

At the primary school level, no important disparities can be noted between the education of girls and boys. However, the differences become more and more apparent with every education level.

In middle school (12-16 years old), the gross enrolment rate for the region of Sedhiou is of 49% for girls and of 55% for boys. These numbers are really low considering education at this age is mandatory. The success rate at the BFEM (final diploma of middle school) differs too with 72% of boys passing and only 66% of girls.

In secondary school, the gross enrolment rate decreases even more, with only 35% of boys of age registered in school, and only 25% of girls. 90% of students enrol in literary studies rather than scientific, partly due to the lack of scientific equipment and teaching staff. In addition, girls are even more underrepresented in the scientific sections.

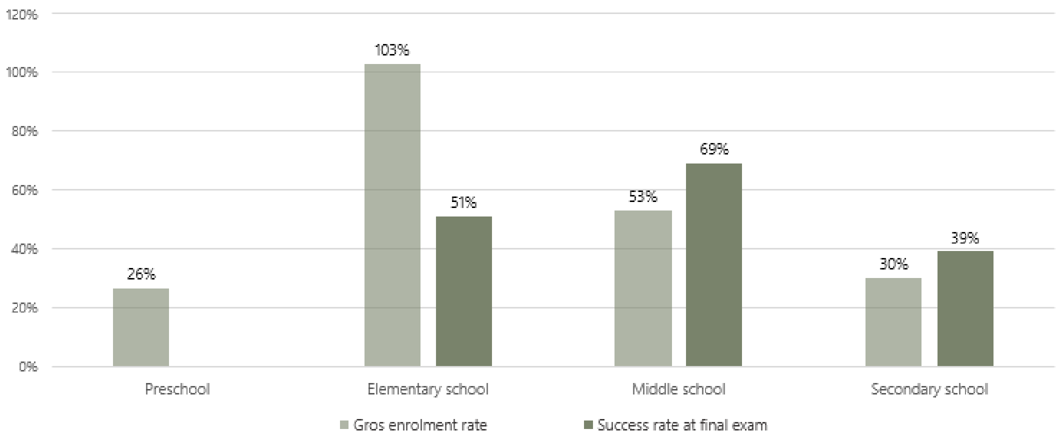


Fig. 1.39- Gross enrolment rate and success rate at final exams in the region of Sedhiou in 2018 @ANSD

Eventually, only 39% of students enrolled manage to pass the Baccalaureat exam, highlighting once again the difficulties of teaching in this context.

The inequalities between genders can be explained by multiple factors : early weddings and pregnancies, cultural bias and the lack of sanitary infrastructure for girls contribute to the gender gap. [34]

The leisure activities for the youth are administered by the Regional Service for the Youth and the Regional Service for Sport. Sedhiou counts 381 youth associations of which 114 are found in the department of Goudomp. The majority of these are "Navetane" movements, which derive from the Navetane championship, an informal sport event taking place during the rain season. However a lot of associations lack built infrastructure and equipment. There is also a reported lack of staff in the Regional Services. Many different projects and programmes for the youth are being created but often lack funding and equipment.

The department of Goudomp doesn't have a lot of infrastructure for the youth, as no "Foyer" has been registered, and the only building dedicated to youth extracurricular activities is the Departmental Center of Popular and Sports Education in Goudomp.

The most popular sports are football and athletics, followed by handball and martial arts. The girls are underrepresented in sports clubs, but their number is increasing. Regular competitions, formal and informal are being organized in the region of Sedhiou demonstrating a real dynamism of the youth. Yet the problems in mobility both urban and rural limit the extent of such events. The region is also lacking in scouting and training staff, that could provide young people with professional careers in sport.

In the region of Sedhiou, lots of young people have also reported interest for art and culture, although the infrastructure to practice these activities are way underdeveloped. Many young people are also engaged in finding solutions to environmental problems. [23]

4.d. Education in Baghere

Baghere only has a primary school, that is mostly out of function due to an advance state of damages. The school was built in concrete with metal roofing and is subjected to important damage while also being uncomfortable for teaching under the tropical climate. There is also an concerning lack of qualified teaching staff, as most teachers are finding work in bigger cities. In this context, the school of Baghere still functions sporadically when the climatic conditions allow it, and teachers are available.

The Mosque of Baghere also offers religious education under the same conditions. Other schools can be found in Tanaff (1,5 km from Baghere), as well as middle schools and high schools. Tanaff even offers higher professional education to study the crafts (baker, blacksmith...). For general higher education, young people have to travel to bigger cities like Sedhiou. However, the families of Baghere rarely have enough money to finance such expenses. Although education is mandatory until the age of 16, 70% of children leave school before secondary school. From a young age, most children work in agriculture and breeding with their families.

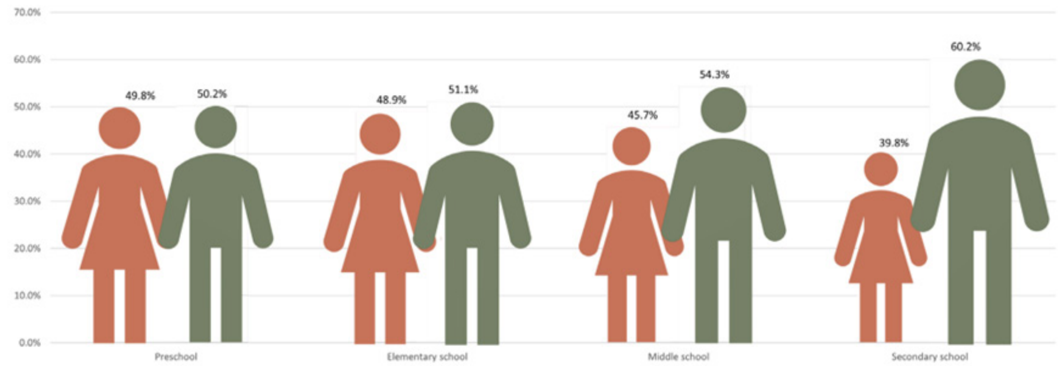


Fig. 1.41 - Gender inequalities in education in Sedhiou @ANSD

The activities for the youth in the village are rather scarce and the only leisure infrastructure is a dirt football field. The only youth centre in the department is in Goudomp, 70 km away.

4.e. Quality design for an African school

The quality of a school relies on different parameters that can influence the learning experience for students :

- Classrooms
- Additional educational infrastructure : libraries, ICT rooms
- Services provided : feeding program, residential, healthcare
- Sanitary facilities
- Local community outreach

- **Classrooms**

The public reached by schools is meant to evolve and many schools become overcrowded. The number of children in a class has little to no impact on learning according to an analysis of the World Bank, unless the students are over 60. Hence, the growing number of students seems to be an opportunity rather than a threat. However, when a class is larger than allowed for in the design process, space and furniture can become unable to accommodate all students. A study by (Uduku 2010) in different schools in sub-Saharan Africa found that the overcrowded classes were the most important factor of school design in terms of impact on the learning outcome. [35] Moveable partitions is a solution developed in some African schools with varying success. It allows the easy extension of the space and adaptation to different uses. However, a bad quality partition affects the acoustic performance of the room. Many schools also have to build additional temporary classrooms to accommodate students, which end up lasting. Designing a building with room for extension and flexibility seems to be one of the best practices in these evolving contexts.

Fig. 1.42 - Class with moveable partitions @R. Wang, R. Wang and J. Yu

A quality classroom should be adapted to the climate. Corrugated iron roofs, for example, can overheat the room without an appropriate ceiling. Some materials like raw earth can also be sensitive to humidity and rain and should be used with overhanging roofs to avoid cracking or even collapsing.

In addition, lighting is an important feature. The openings should be designed appropriately in order to provide sufficient lighting. As the desk's height varies according to the age of the children, the openings can be different too. But the light should not be too bright either or it could be blinding. Solar protection techniques can be implemented in the design to monitor the quantity of light entering the classroom.

As mentioned earlier, the acoustic performance is an important aspect of a classroom. Sheet metal roofs give a bad acoustic and should be implemented with appropriated ceilings. The materials of the walls can also change the acoustic of the room.

Fig. 1.43 - Classroom with adaptable louvers to provide good lighting @Kere Architecture

- **Additional educational infrastructure: libraries, ICT rooms**

Some schools provide additional educational rooms, such as libraries or ICT rooms. Although there is proven benefit to these facilities, they need adequate funding. Many schools lack books or IT equipment to furnish these rooms. In other cases, the lack of staff leads to underuse of the facilities. Furthermore, both books and computers can become obsolete and need regular replacement. With the rise of individual electronic devices, updated knowledge becomes accessible to most. The libraries could therefore become open spaces furnished for individual use of technology. This way, these spaces can also be more versatile and used by the community during out-of-school hours. It is the case for the library of Vukani primary school, in Cape Town South Africa, which serves as a classroom for adult evening classes.[35]

Fig. 1.44 - Vukani Primary school in Cape Town @Flikr

- **Services provided : feeding program, residential premises, healthcare**

Additional services can be a great incentive to invite children in school. Providing a free meal to students encourages poorer families to send their children to school and ensures the quality of nutrition received. This way, income-based disparities can be tackled, and every child has access to a healthy diet, which he can reproduce as he grows up.

Nonetheless, a feeding program can be costly and requires appropriate premises and equipment. For stocking and preparing the meal, the school should have a hygienic kitchen with running water. A cafeteria space separated from the classrooms helps in reducing the risks of disease transmission. It can also be an open-air cafeteria if needed regarding the fundings. The kitchen and food hall can be lent to the local community for events making the investment cost-effective. To supply the ingredients, some schools have a community farm attached to their premises, that can also serve educational purposes. [36]

Depending on the context, dormitories can be a worthwhile addition to a school, especially in sparsely populated regions, where students have a long journey from their respective home. In these cases, a particular attention should be on the security of these premises.

A sickroom is an effective improvement of a school complex. Many treatments are cheap and don't require much training but can all the same have a tremendous impact on a child's health and development. The treatments provided in such facilities include deworming and eye screening. Free care can also be an incentive for parents reluctant to send their child to school.

Fig. 1.45 - Kiirua Seventh-day Adventist School in Meru, Kenya @Maranatha

- **Sanitary facilities**

Sanitary facilities are a key topic in school designs. A study by Asadullah in 2006 found that the presence and type of toilets have influence over the enrolment and retention of students in primary school. In many case studies, the installations were unfortunately found unsanitary. Different typologies of latrines can be found in African school.

The flush toilets are not the most usual and they can sometimes become out of service when vandalized, broken or subject to leakage. The maintenance skills and funds are lacking in most villages for this type of installation.

The pit latrine are the most common facilities found in schools. They are located in separated buildings away from the classrooms and can vary from a simple hole to a ventilated improved pit latrine (VIP). This last model was theorized and deployed by the UN and provide better sanitary conditions through the simple addition of a ventilation pipe. The pit latrine also requires some simple maintenance: emptying and cleaning of the toilet. [37]

During her Edqual school buildings research, (Uduku 2010) found that maintenance of the sanitary installation was lacking in most schools leading to hygienical risks. Students are hence usually using natural areas around the schools as open-air toilets. [35]

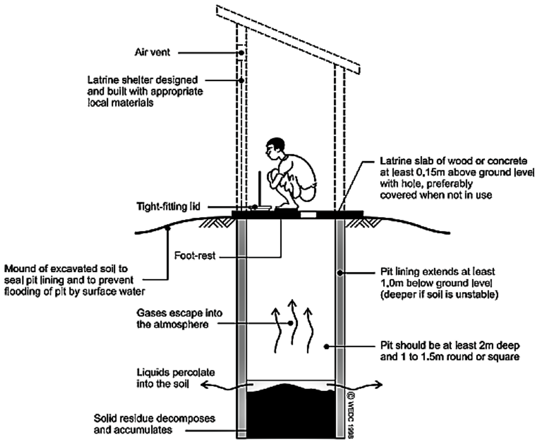


Fig. 1.46 - Pit Latrine @HARVEY et al.

- **Local community outreach**

Schools can be strongly linked to the local community through different functions. When the community is involved in the school, parents are more likely to check their children's attendance, and the premises are better maintained. As the school can still be a symbol of colonialism and top-level policy, sharing the infrastructures and their benefits with the whole population is a key success factor for the acceptation of the education system. [32]

A first way to involve the population is during the design and construction process. Different experimentations in that direction have obtained good results in Africa. In Benin, community driven development was experimented between 2000 and 2004. The classrooms' construction was handed to the communities with a funding given by the World Bank. During that time period, the local population built twice as much classrooms as the government over a similar period and for 20% less costs per unit. After auditing, most premises were judged satisfactory. The same kind of policy was applied in Zimbabwe and resulted in a sudden increase of the enrolment rate.

As mentioned above, some facilities can be shared with the community such as ICT rooms and libraries, which can be used to educate adults as well or to host cultural events. The food infrastructure: kitchen and cafeteria can also be the stage of gatherings strengthening the community bond.

Fig. 1.47 - Teacher consultation workshop @ARUP

The community can also participate in the educational curriculum. The local skills such as farming, cooking or crafts can be taught at school too. This can convince parents that will be reassured that their children are learning useful skills. The basic knowledge to be taught in school: reading, writing and arithmetic, can also be contextualized locally by linking the educational support to the traditions and activities of the village.

Introducing a community farm for the school feeding program has been proven successful in many rural schools. It both supplies the cafeteria in healthy ingredients for little money and includes the villagers in the running of the school. In rural areas, most inhabitants are farmers, so little to no training is required for running the community farm. It can also become an educational support to teach about nature, food, or farming. Finally, the surplus of food that doesn't get used by the feeding program can be given back to the community in gatherings creating even more social link and maybe even helping some poorer families. [38]

Fig. 1.48 - Vegetable garden in school, Tanzania @Tloma Primary school

II. VERNACULAR ARCHITECTURE

II. VERNACULAR ARCHITECTURE

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1. VILLAGES IN SENEGAL

1.a. Traditional villages

Originally, villages consisted in a gathering of families, generally from the same ethnic group, living on the same land. They were usually founded by an important member of a family, often religious, that would decipher new lands to devote themselves to God. For instance, this was the case for the village of Baghere. The site would be selected according to its ability to provide a good shelter against meteorological conditions and in particular the different winds. It also had to present a nice vegetation that could be used not only to feed people but also to build dwellings. Their settlement had a molecular organisation with several centralised compounds, belonging to members of the same group, dispersed and linked by footpaths. The boundaries between villages can be difficult to be identified. Indeed rather than being physical edges, boundaries often rely on the relationships between families. [1]

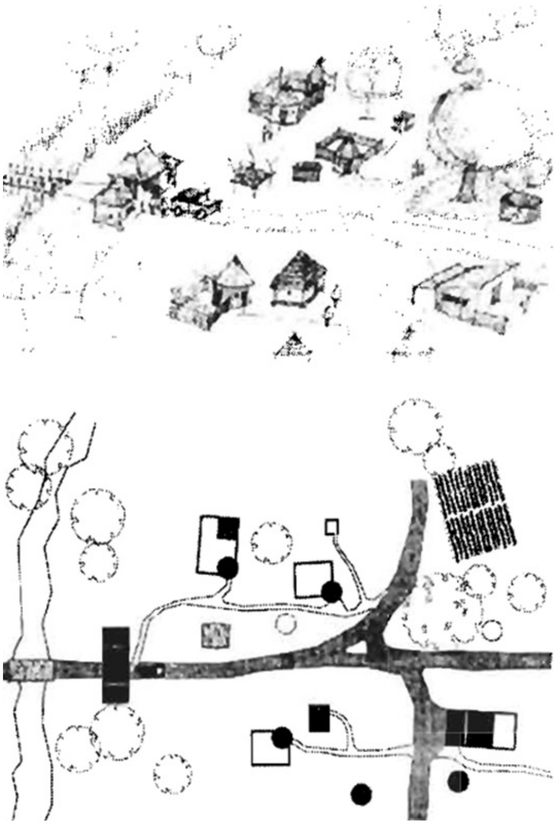


Fig. 2.1 - Plan and isometric view of a part of the Banoka village @Roodt

Fig. 2.2 - Peul settlement Ndioum, Senegal @KaBa

Fig. 2.3 - Traditional village in Senegal @Wanderlust

For nomadic people, there were ephemeral dwellings. As, nomadic lifestyle turned into sedentarism, villages also settled down for a longest period of time. Nowadays, villages in Senegal are not only a group of persons but also the core cells of the territorial administration; villages on the same land are gathered in rural community and ruled by a chief appointed. In 2013, they were 149 584 villages in Senegal. [2]

The vernacular architecture and village organisations of Senegal are the result of the traditional way of building being developed and modified over time. Indeed, all the different ethnies that inhabited the territory had to adapt their habitat. It is mainly a dwelling architecture, closely linked to the extended family, the basis of social organisation, and thus strongly influenced by the social and economic changes occurring in the communities. The village are therefore at a human scale.

Each culture configures its housing according to a particular system of life and occupation of the territory, with distinctive identifying features. Therefore, in this context, the cultural and landscape value of the built vernacular environment is particularly evident.

Indeed, the organisation of villages relies a lot on the environment and on the climate which influence the adaptation of the settlements to be the best adapted to local conditions. For example, villages located in the Sudano-Guinean zone, as Baghere, must be adapted to a tropical climate generally hot, humid, and uncomfortable but also to the wind which direction changes throughout the year. Besides, favouring cross ventilation is a crucial asset and can be implemented either in the house configuration as in the typical Diola huts, which are organised around an open living space, but also in the village organisation with the scattering of houses from one another.

Villages are closely linked to agriculture. Therefore, we can often observe a general spatial layout shared by a lot of sub-Saharan villages in which the centre of the village is closely surrounded by permanent cultures. Then a second circle can be defined around these fields composed of temporary fields, orchards, and forests. Many villages are built around or close to rivers to provide irrigation to the cultures. The pathways traditionally are not in a straight line but follow more organic trajectories. They merge together rather than crossing each other. This typical layout can be seen in the example of the village of Pathiab in Fig. 2.4.

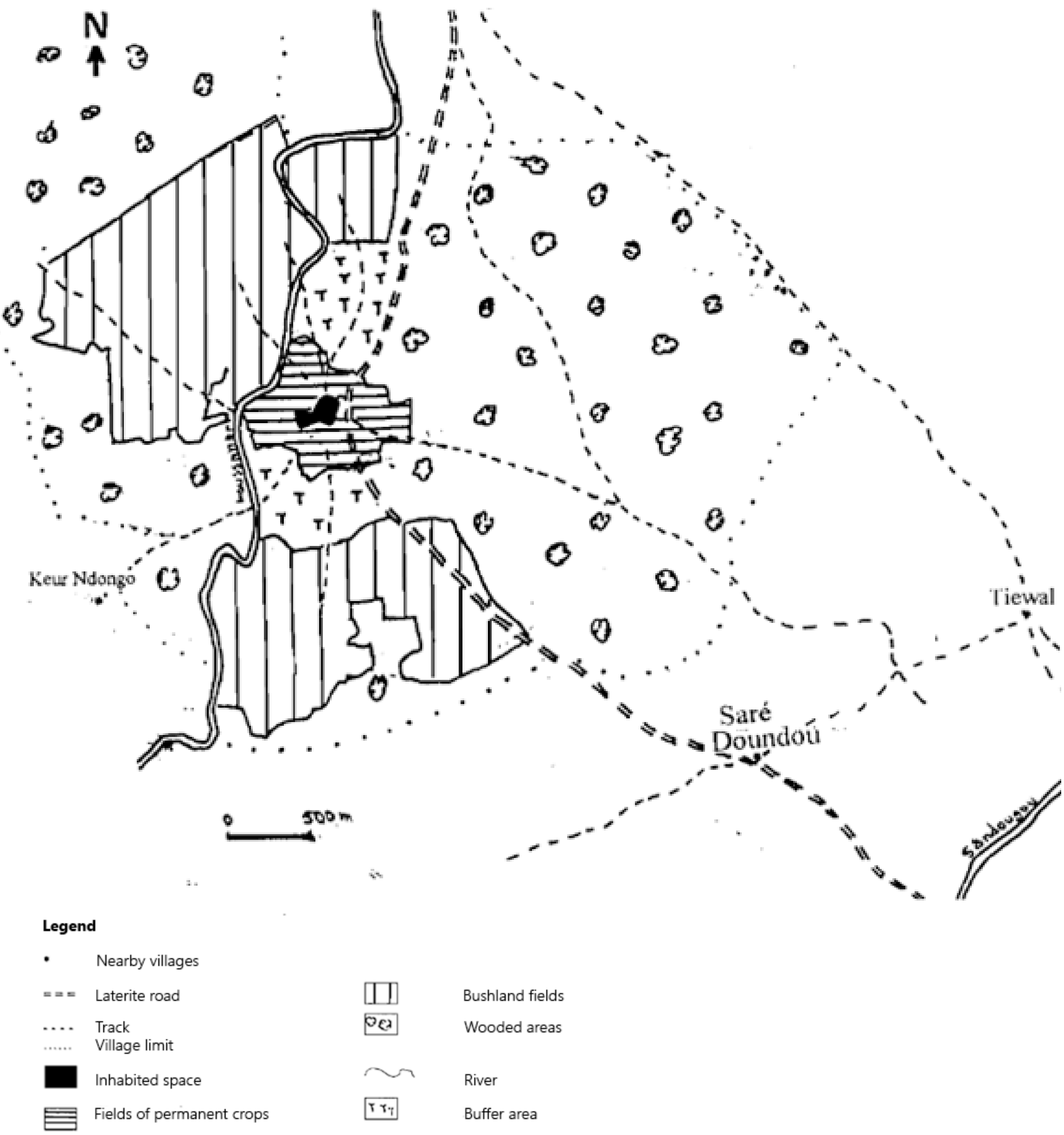


Fig. 2.4 - Schematic organization of the village of Pathiab, Senegal @A. Coly

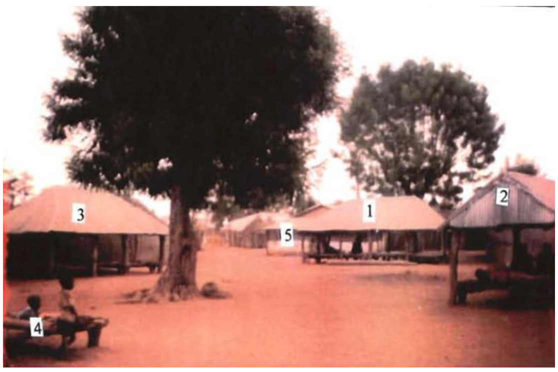
1.b. Mandinka villages

Mandinka's villages are characterised by a strong traditional organisation that is emphasized through the functioning of the village and its political and social organisations.

The morphology of a village is similar to a heap of houses arranged quite in a compact way around a central space. When needed, the village tends to extend itself towards the exterior. The centrale space is very important in the Mandigues culture as far as it is the meeting point for the village assembly. On this piazza, they can be three shelters for men only, called "bentégno" destined for a specific range of age. The first east shelter is for the elderly and the village meetings and councils, the second East one is for young adults and the West one is for the young boys. Women can't sit under these shelters and must bring their own chair to attend events.

Regarding the housings, the buildings are either square, rectangular or circular with a straw or corrugated metal sheet depended on the local vernacular architecture and the wealthiness of the families. [3]

The infrastructures generally include:
- A health hut for primary cares
- A well
- A little shop
- A mosque
- A school



LEGEND :
1. Shelter of the elderly
2. Shelter of young adults
3. Shelter of young boys
4. Bench of the children
5. Mosque

Fig. 2.5 - Centre of the village of Pathiab, Senegal @A. Coly

2. VERNACULAR ARCHITECTURE

Vernacular architecture can be defined as a type of local or regional construction, using traditional materials and resources coming from the building area. This type of architecture is therefore closely linked to its context and heavily influenced by its geographic and cultural specificities. Vernacular architecture is hence an illustration of one place's identity.

2.a. Role of architecture

The vernacular constructions in the region of Casamance present an important diversity. Although every ethnic group has its specificities, they share some common architectural principles. First, the main functions of the buildings are shared: traditional constructions include houses, agricultural buildings, such as granaries, and religious constructions.

- **Housing**

The concept of the house is different from the European vision of the home. The house welcomes from one to a hundred individuals, all centered around a common male ancestor. It is thus made of multiple units. In this extended family, each member is given a different role, and those are also reflected in the architecture of their home. Every unit in a settlement reflects its owner's individuality whilst still sharing a common basis. This type of architecture is therefore both personal and collective. In fact, the house expands when the family does, and diminishes with the losses. It is a true illustration of its inhabitants. The construction and maintenance are part of the community rituals, and a static house traditionally signals a family in disarray. The relation to the buildings is therefore human, and every man is a builder.

The house is where people sleep but is rarely a place to live in. It is seen as an intimate place with very few openings, and the transition from inside to outside is usually blinding. Only the women spend some time of the day inside, to cook and do other household chores. In fact, the units are often the properties of the women, and the man sleeps in one of his wives' unit.

Hence traditionally African people live outside, and the house is not limited to the built environment, but the external spaces are an integral part of the living spaces. They are often developed with shading, fences and seating spots and serve as transition between buildings. In modern settlements, this way of living tends to shift towards a more indoor life as villages become denser. [4]

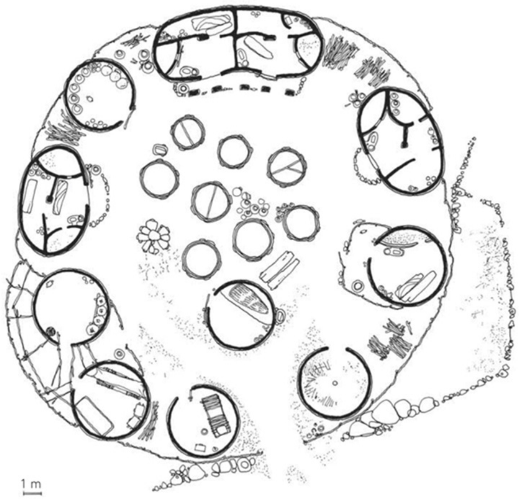


Fig. 2.6 - Plan of a Gidar house, Tchad @Seignobos

- **Granaries**

The granary is an important element of the community. It is usually decorated and difficult to access. Depending on the ethnicities, the access can be limited to certain people, such as the first wife of the family's chief. Stone or wood foundations are used in these constructions in order not to spoil the crops with water. The food is stored up high, so that it is inaccessible to animals. The granary holds the food reserves for the family and is therefore seen as a highly valuable, almost sacred, place.

- **Religious buildings**

As far as religious buildings are concerned, they are mostly recent additions. The ancient animalist religions mainly don't use spiritual buildings. In Senegal, nowadays, the majoritarian religion is Islam, brought by the ethnic group of the Toucouleur. The traditional mosques of the Toucouleur were built based on Mohamed's house in Medina. The façade contains 3 doors opening on a courtyard. A small cubic structure, covered by a conical straw roof emerges from the façade and hosts access to the roof for the call to prayer. Over time, some Toucouleur elements were added such as the vestibule and bas reliefs on the façade. In fact, they were hybrids between indigenous and Muslim constructions. The Toucouleur traditional mosques are built in clay. In the region of Casamance, however, most mosques are recent and are built in concrete with the characteristics of Arabic constructions. [5]

Fig. 2.8 - Mosque of Baghere @Balouo Salo

Fig. 2.7 - Masa granaries, Tchad @Seignobos

2.b. Vernacular construction materials

- **Wood and vegetal products**

In a tropical climate as Casamance, the building form usually includes a thatched roof with big overhangs, either covered in straw or palms, to face the tropical rain season. Cylindrical homes are usually found in the savannah regions and rectangular homes in the tropical forest even though the shapes are also linked to the ethnic groups and their building experience. The tropical climate also implies higher humidity levels, therefore the need for ventilation is even more important. The traditional houses include this aspect, often by the raising of the roof from the walls.

The region of Casamance provides luxurious vegetation. We can therefore find vernacular dwellings built with wood, branches, and leaves, which are also less subject to degradation from humidity, than earth buildings. Wood is a good structural element, while palms are generally used for roofs. Some buildings made of clay are also reinforced by a vegetal armature for this very reason.

Fig. 2.9 - Thatch roof construction @Seignobos

Fig. 2.10 - Construction with adobe bricks and thatch roof @Balouo Salo

- **Raw earth**

Earth is a traditional building material in Africa, used by most ethnic groups and the Casamance region is no exception. It is particularly well-adapted to savannah climates and is used in different forms:

- Wattle and daub : Referred in west Africa as 'banco', it qualifies the use of clay as a filling material on an existing structure made of wood. The earth used in wattle-and-daub is mixed with manure or chopped straw. The microbes contained in these supplements helps the earth to cement.

- Cob : The earth is in this case a structural material. The shape of the wall is first traced on the ground. Then, walls are modelled by piling up soil clods by hand on a base. These earth clods are placed by layers of 25 to 50 cm high and 40 to 60 cm large. After each layer implemented, small conical shapes are created on top of it to anchor the next one. Between each strip, the earth is left to dry. The earth used in this case is usually combined with straw to increase the mechanical resistance and the isolation of the material.

- Adobes: Raw earth bricks, moulded and dried in the sun are assembled with an earth mortar. The mixture used to make the bricks usually contains straw or gravel to enhance the structural integrity. This technique is the one most developed in the region of Tanaff.

The roof of these buildings is almost never supported by the earth walls. An additional wooden structure holds the roof made of earth, straw or wood. [6]

2.c. Traditional ethnical constructions

The main ethnicities found in Casamance are the Mandinka, the Peuls and the Diolas. They each have their own characteristics in terms of traditional building techniques and forms.

Fig. 2.11 - Mandinka village, Soudan @Collection Générale Dakar

- **Mandinka**

The Mandinka people are primarily farmers, but some are also craftsmen (woodcarving, leather, and metal working, weaving and dyeing). They live in a caste-divided patrilinear society. Traditionally, Mandinkas were divided in 3 castes: the slaves, the caste-members (bards, blacksmith, leatherworkers, and Islamic poets) and the nobility. Although slavery has been abolished in the late 1800s, the Mandinka society is still divided in these 3 categories, and one cannot easily marry someone from another caste. Every family is leaded by the oldest male descendant, and the village is under the authority of the male leader of the oldest settlement. The Mandinka also have an important culture of storytelling through music and poetry, with the griots : musician and singers that transmit the history of the community through generations.

As Mandinka people were traditionally farmers, their settlements are surrounded by their fields. The traditional Mandinka dwellings were built mostly using adobes or cob with a thatched roof. They were in the form of individual cylindrical or rectangular units with straw roofs grouped together in a circle. The dwelling was also enclosed by a wall. The decoration of the houses was used as a sign of belonging in one of the societal groups of the Mandinka society.

Fig. 2.12 - Mandinka dwelling in Mali @W. Forman

- **Peuls**

Traditionally, the Peuls are cow breeders. Therefore, they used to be nomad people, guiding their flock in different regions according to the season. They would exchange goods with the local population against meat and dairy products, which has given them a reputation as a sociable people.

Being nomad people, their settlements were composed of movable constructions. Their houses were made with detachable wooden structures, without foundations and with lightweight materials that could range from animal skins, straw, woven mats or fabrics. One of the most common structures were domes built with branches and covered in straw. They always had a wooden fence around the houses to keep their herd.

One of the striking characteristics of the traditional house of the Peuls is the entrance of each unit. The opening of the door is small and invites the one who enters to bend over. It is then followed by a low wall to be stepped over. This system shows the importance of the passage in this culture. It also makes sure that no one can enter uninvited without being seen, especially in a woman's house. The custom even says that a child can leave his mother's hut only when he is old enough to climb over the wall by himself.

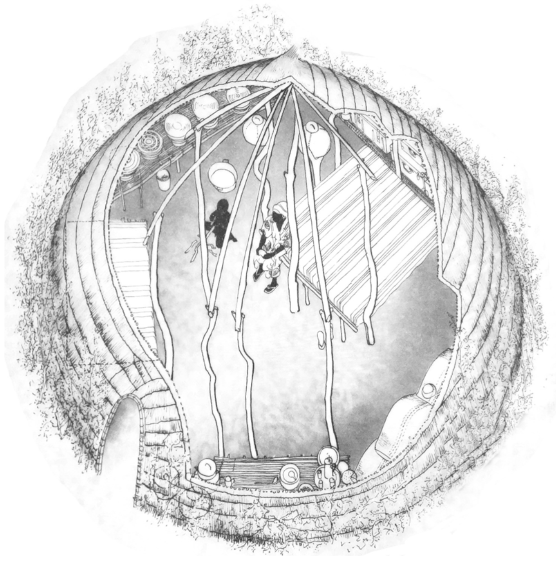


Fig. 2.13 - Sketch of a Peul dome @J.P. Bourdier

The interior of the house is organized in two halves : the woman's half and the man's half. The bed is found in the middle, right ahead of the entrance. On the left, in the feminine part, are found the bed for an eventual child and all the material to take care of a child as well as the water supplies. On the right side, the tools, the wood reserve and the hearth and the pots are placed along the wall.

Fig. 2.14 - Peul dome @B. Sana

- **Diola**

The diolas were traditionally cultivators of rice, fishermen and makers of palm wine. The vernacular Diola dwellings are very diverse, as they were known as good builders. They notably built some houses with a unique characteristic: the impluvium.

The impluvium is a central courtyard defined by multiple independent flat roof houses organized in a circle. These independent buildings are covered with a unique double sloped thatched roof that collects rainwater in the impluvium. Holes are made in the roof of each earth unite to allow for poles to get planted into the ground and act as an independent structure for the straw roof. This roof allows natural ventilation and protects the clay houses from the sun's heat. Each individual unit is built with adobes and contains a sleeping room and a storeroom. Outwards, each house has a private veranda and a private fenced garden. Inwards, each unit has its own jar to collect water, but the verandas are communal and used for daily activities. The impluvium house is a very sophisticated construction which requires a lot of community effort to be built and maintained. It is therefore progressively disappearing from Senegal, as other traditional constructions. Other types of traditional Diola dwellings mostly appear as separated spaces grouped around a central courtyard, highlighting the sense of community of this ethnic group. [5]

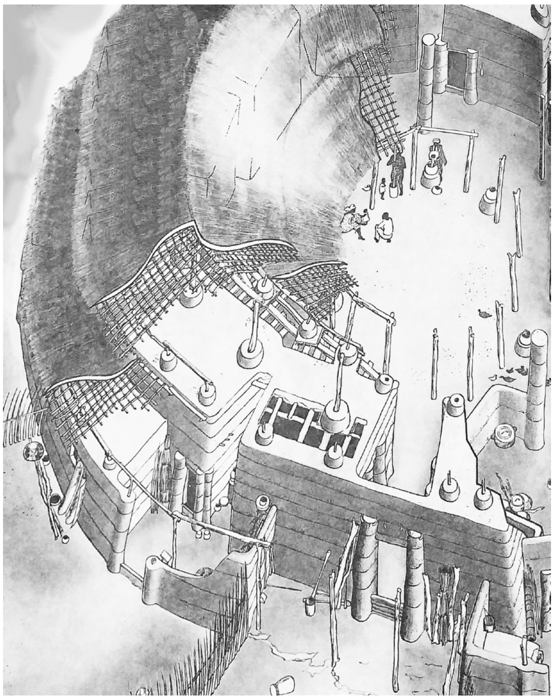


Fig. 2.15 - Sketch of an Impluvium@J.P. Bourdier

Fig. 2.16 - Aerial photograph of an impluvium @M. Ascani

3. BAGHERE VILLAGE

3.a. Spatial organisation

The village of Baghere is organized around one main street coming from Tanaf across the river and continuing towards Sardiner where boats cross the Casamance river to Sedhiou. All the public buildings and spaces are found along this street visible in yellow in Fig. 2.17. Some secondary streets on the right lead to other houses and fields. The most important building surely is the Mosque, set apart by slightly larger dimensions and its characteristic minarets. It is found in between many shops and houses tightly packed along this major axis. As the road continues, the buildings are progressively mainly residential, and more widely spaced.

Apart from the crowded center of the village, where the buildings are simply placed along the streets, the buildings of Baghere are arranged into settlements. Buildings are grouped together to form a household sometimes encircled by a wooden fence. The urban fabric is sparse and can be described as informal. The living spaces of each household expand outdoor according to local customs.

The village is surrounded by fields for the cultivation of rice near the river and wheat further from it. Indeed, agriculture is the main occupation of most of the village's inhabitants. Around the fields, forests cover the surroundings of Baghere. The village of Bakidiouto is found in the near proximity along the river.

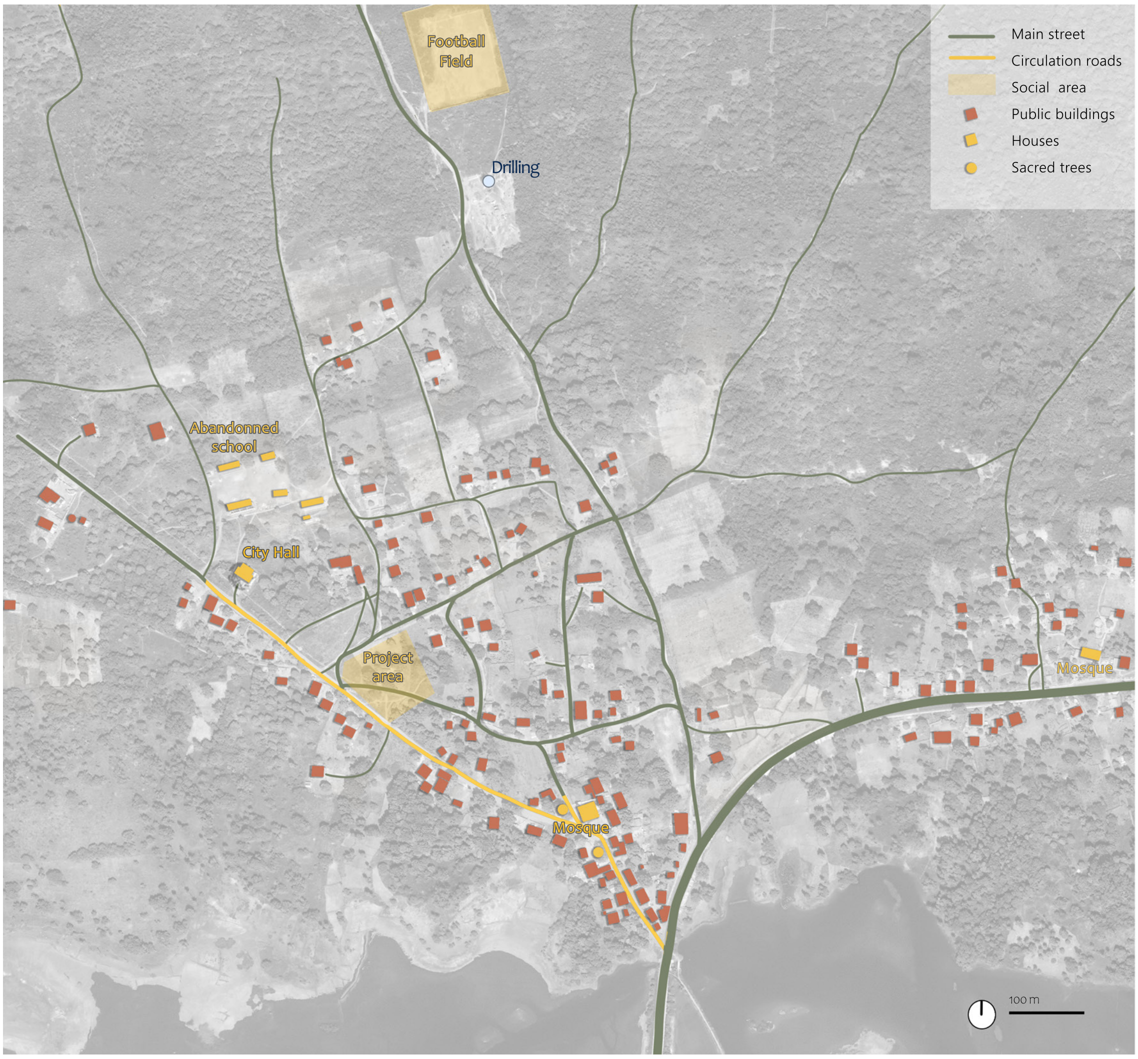


Fig. 2.17 - Conceptual map of Baghere

3.b. Infrastructures

The main infrastructure is the Mosque, in the centre of the sacred village. Other public buildings are the townhall, the school and the health centre. The town hall is found on the main street close to the former school. The school is not functioning consistently due to a lack of teaching staff and its advanced damage state making it unusable A covered marketplace was built in the village but the market did not receive the expected success. Besides, with the help of Balouo Salo charity, more infrastructures projects are being designed and built.The main drilling is in North of the village, but other smaller drillings in the village provide drinkable water to the inhabitants. A football field is also found near the drilling.

Fig. 2.18 - Healthcare centre of Baghere @Balouo Salo

Fig. 2.19 - Town Hall of Baghere @Balouo Salo

Fig. 2.20 - Healthcare centre of Baghere @Balouo Salo

3.c. Social spaces

The road is made of dirt and many vehicles are old and badly maintained, therefore the speed of the vehicles is often greatly reduced. Hence the streets become a social space, where people meet and sometimes do commerce. At the first road junctions, two sacred trees are found. In this tropical context, the public space is defined by shading, and the trees become a place of formal and informal meetings.

The football field is also an important social space. Young people gather there to play and socialise. During the summer, the Navetane competition brings the community together.

Fig. 2.21 - Aerial view of Baghere @Balouo Salo

4. Architecture in Baghere

4.a. Modern buildings

Nowadays, more and more buildings are being redone in bricks and cement. In fact, these materials are seen as a sign of modernity and wealth. They also require less maintenance than clay walls and straw roofs. The latter require regular monitoring and repairs or replacement in the case of the straw roofs whereas cement bricks and metal roofs last longer with minimal maintenance. However, the thermal insulation capacity of the earth and straw are better adapted to the local climate. If employed incorrectly, the metal roof can provoke overheating of the building and important noise in case of rain. Moreover, these new materials have an important ecological footprint while those of clay and straw are almost none.

Baghere is no stranger to this trend. Most buildings are made of concrete foundations, cement bricks covered by cement plaster (usually white), and metal roofing, supported by a light metal structure. All the public infrastructures, including the mosque, the town hall, the health centre and the school, have been built using these new materials and techniques. Rebuilding one's house with these 'modern' materials is viewed as an affirmation of one's wealth and social status.

Fig. 2.23 - House in concrete blocks with a metal roof @Balouo Salo

4.b. Traditional buildings

However, a few traditional buildings are still in place in the village. They are made of a wooden structure, earthen walls, and a straw roof. They mostly are of circular shape with a diameter of around 8 m. The buildings are grouped together in settlements circled by wood fences. These buildings are also distinguished by the orangey brown colour of the earth that sets them apart from the white modern buildings.

Some buildings are also a mix between traditional and modern constructions, with earthen walls topped by a metal roof for example. This type of construction benefits from advantages from both materials and way of construction. They are mostly square buildings. White plaster sometimes makes them fit in along the cement buildings whereas in other instances, the earthen plaster makes them resemble the traditional constructions.

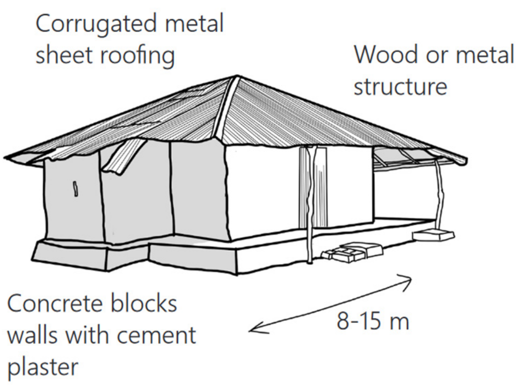


Fig. 2.22 - Sketch of a modern house

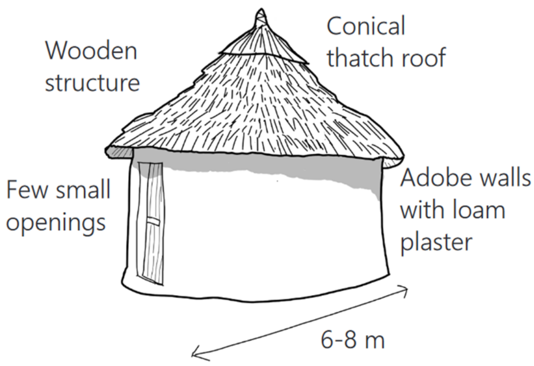


Fig. 2.24 - Sketch of a traditional house

Fig. 2.25 -Traditional house in Baghere @Balouo Salo

Fig. 2.26 - House made of adobe blocks with a metal roof in Tanaff @Balouo Salo

4.c. Common characteristics

All buildings have rather modest dimensions, from 8 m to 15 m for the housing blocks and up to 20 m for public buildings. All buildings in Baghere are single-storey, and have rather low walls, from 2 to 3 m high at their lowest point. The more traditional buildings have a circular plan and a conical roof. As they are becoming ever less common, most buildings in Baghere are square or rectangular, with hipped or gabbled roofs.

Most houses have few and small openings. In traditional buildings this helps maintening the structural integrity and avoiding heat gains in the building. It is therefore in the local customs to live in rather dark houses. Most modern houses still have few openings. For public buildings however, larger and more openings can be observed.

III. BUILDING WITH EARTH

III. BUILDING WITH EARTH

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1.GENERAL KNOWLEDGE

For centuries, raw earth has been the most used construction material. In many places in the world, raw earth building is part of the culture heritage of the country. This is the case in Africa where many ethnic groupd have coexisted and have always built using local materials respecting nature. It is a versatile building material in the same way as cement, concrete or stone. It can fulfill identical functions such as carrying, crossing, protecting, decorating and has great thermal, ecological, economical and structural qualities. Over time, its use as a building material has evolved and construction techniques have been improved or invented.

Nowadays, raw earth is more and more often replaced by concrete, even in countries where this last material is poorly adapted to the climate. This phenomenon dates back to colonisation and since then, raw earth suffers from a poor image. However, some ancestral techniques remain and new techniques are developped to adapt raw earth to modern constructions and meet their requirements. According to the function required and to local soil characteristics, various techniques can be used such as rammed earth, adobes, poured earth, cob, compressed bricks and more.

Besides, many scientific studies are carried out on raw earth and its properties, to understand better and improve its characteristics as a building material. Some architects also try to reimplement raw earth architecture in some places using ancestral or modern techniques. These studies also help in reintroducing the material in many construction projects to encourage sustainable architecture. Indeed, there is an urge in using more ecological materials in buildings and construction has a key role in the ecological-socio-economic development of a country. It is responsible for promoting a sustainable built environment and more inclusive societies. It can also improve people's quality of life, economic growth and job creation. [1] In a context in which the concept of resilience must replace the context of sustainable development regarding the alarming evolution of biodiversity, global warming, economic and financial aspects, using raw earth as a construction material can be a way to reach it. Not only is it a great sustainable material that is low-carbon but also it can really help to reconnect with nature and culture.

1.a. Historical use in the world

Used for more than eleven millenniums, raw earth is one of the oldest construction material in the world that has contributing to the culture heritage of many countries. One third of the population still lives in a raw earth building [2] and among the 1199 buildings on the UNESCO world heritage list, more than 10% are made in raw earth. [3][4] Building in raw earth involves using local materials and techniques. This gave rise to an extraordinary variety of vernacular constructions and techniques which explains why earthen architecture is very linked to its territory. A case in point is the Great Wall in China which has a very heterogeneous aspect due to the different types of resources available among the local materials (pisé, clay bricks...).

The typologies of buildings are also very diverse : individual houses, industrial buildings, healthcare centres, schools, agricultural hangar, defense use... The large variety of use, localisation and techniques of construction offers a real

Fig. 3.1 - 3D printing round houses in raw earth in 200 hours @TECLA

Fig. 3.2 - Earthen architecture repartition in the world @ Anger.R e Fontaine,L

Fig. 3.3 - Portion of The Great wall of China made in rammed earth @Wikipedia

Fig. 3.4 - Portion of The Great wall of China made in clay bricks @ootravels.

wealth in terms of architecture and aesthetics. These earthen architectures really underline that the material is the flesh of architecture.

These buildings are mainly found in Africa, Middle East, Asia, Latin and South America. However, in Europe this practise nearly disappeared in current constructions but still some ancient buildings remain. Indeed, in France for example, it represents only 10 % of the new buildings these last five years and 15% of the French architectural heritage but it still represents more than two million of crude earth buildings. [5]

Nowadays, to respond to current social issues, architects of all continents reimplement raw earth in architecture. For instance, in Europe, Martin Rauch combined rammed earth with clay brick to manage water erosion. In Latin America, Marcelo Cortes, explored the adaptation of raw earth techniques to paraseismic resistance. In Asia, Anna Heringer adapts traditional building methods to create child-friendly spaces. In Africa, Francis Kere shows how to create economical and simple architecture adapted to school. Finally, architectural awards such as Terra award also encourages the renewal of raw earth as a building material.

1.b. Composition of raw earth

- **Soil composition**

The composition of the soil is explained by its geological history. Indeed, it is created by nature as a result of the breakdown of the organic elements. These material fragments, known as sediments, accumulate and undergo a series of chemical and physical processes, called pedogenesis. This process will give to the soil its physical and chemical properties.

The soil creation process explains the layered composition of the earth and their different characteristics. From top to bottom, the first layer is the top soil corresponding to the vegetal earth very rich in organic elements. This layer is not used in construction as its composition doesn’t give sufficient solidity. Then comes the second layer called subsoil used in construction and last, the last layer with the underground composed of the bedrock. [6] Thus, in an earth sample, one will find different organic elements with different sizes. Pebble, gravels, sand, silts and clay are defined by their diameter. Their proportions impact the composition as shown in fig 3.8. The vertical axis represents weight by percentage of the total of each grain size, which in turn is plotted on the horizontal axis using a logarithmic scale. [7]

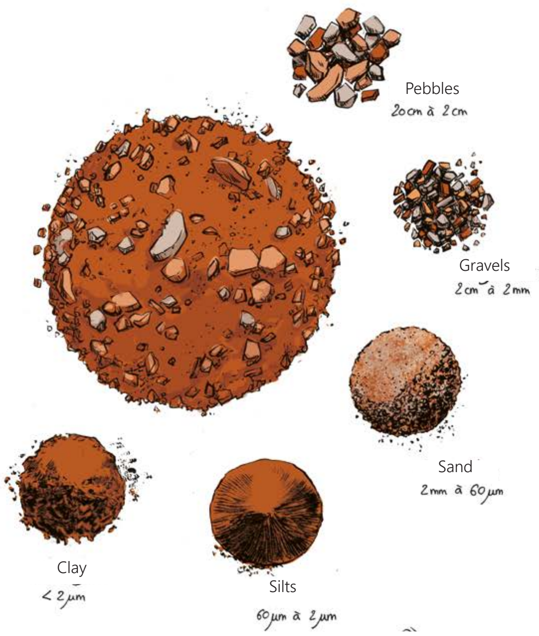


Fig. 3.5 - Soil components @P.Sémon

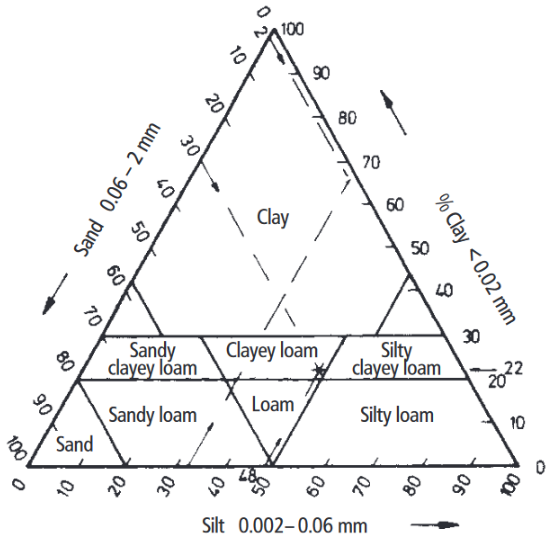


Fig. 3.6 - Soil grain size distribution by Voth 1978 @G.Minke

The little rock fragments form the granular skeleton and give to the sampling its rigidity. Meanwhile, clay particles, recognizable by their leaflet or platelet forms, act like a binder and allow the material to be cohesive. The soil thus formed is made up of grains and voids, most of which are filled with water. These three elements are essential for its stability and resistance in construction.

The density of raw earth materials depends on the techniques used. Freshly dug soil has a density from 1000 to 1500 kg/m3 while compressed earth as a density between 1700 to 2200 kg/m3. [7]

"Metal rusts, wood rots, cement and stone are chemically attacked. Soil is made up of elements that have already been altered and cannot deteriorate any further. "
Anger R, Fontaine L [4]

Being already a degraded material, the earth used in construction will not alter over time if properly protected from water. Furthermore, the building is part of the geological life cycle, since once abandoned, it will change with the wear and tear of time and return to its initial state.

- **Clays**

Clays are organised in different families regarding their specificities, shapes and structures. However, they have in common one characteristic: they are made with microscopic leaflets whom thickness is less than few atoms.

They have a layered structure consisting of three or four planes of oxygen atoms between which are inserted atoms of aluminium and silicon making clays silicates. [8] They are the finest constituents of the earth and their small size is responsible for their cohesion force. Indeed, their small size and their plane surface enable to multiply the capillary forces of the water and thus link all the earth components. However, interstitial water reduce the links between binder particles in the material. It is only once the water evaporates that stronger chemical bounds that imply denser inter-particle arrangement can result.[9] This can be explained with the Lambe's model applied on compacted soils. As the material dries, the distance between two clay platelets will reduce and become little enough so the Van der Waal prevail and imply clay flocculation and create the structure. [10] [11] Clay is thus the binder of the earth in the same way as cement for concrete.

There are different types of clay that can be almost all classified through four main families: kaolinites, smectites, chlorites and illites. Illites is the most used clay in construction. Indeed, Kaolinite is a non-swelling clay known for its use in porcelain and paper pulp and is easily washed away by rain and not the best for construction. Smectite is a swelling clay that will crack on drying thus very bad for construction. Indeed, it has a poor cohesion that it is mainly due to their charge and water can penetrate this network of membranes and make it swell. Finally, illites is the most used clay in construction as it is made up of inseparable sheets and carries a strong negative electric charge.

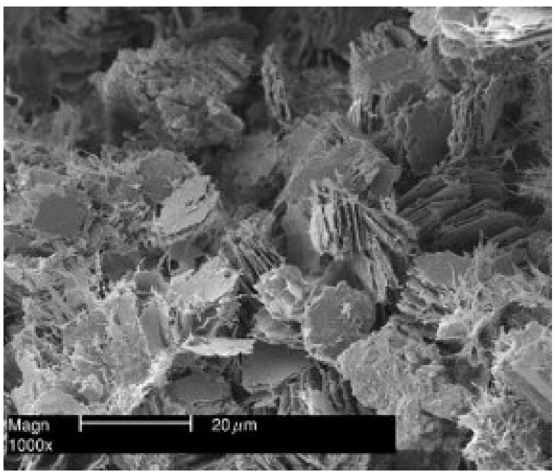


Fig. 3.7 - Fracture surface scanning electron microscopy (SEM) image of illite pseudomorph of kaolinite @J.M. Huggett

1.c. Water influence

- **Water cohesion**

Water is a key element in the making of the building material as it activates the binding forces of loam. Indeed, it impacts chemical bonds as far as interstitial water influences on the material resistance. The stress implied by it is due to Stefan adhesion. The water contained between two parallel plated exerts a normal force proportional to the distance between the plates. Some tests shown that rate sensitivity in tensile strength can almost be multiplied by two when samples are saturated regarding normal cured concrete. [12][13] The water content of a material is very important also regarding shrinkage and swelling during the drying process. Indeed, swelling occurs if loams loses its solid state in contact with an excessive water proportion.

- **Vapor permeability**

The vapor permeability of raw earth is very important. Indeed, considered to be between 5 and 20, the presence of water in wall enables to regulate humidity. A raw earth wall is never fully dry because of the water retained by the clay particles. Raw earth contains around 2% of humidity thus 15 litres per square meter for a 40 cm thick rammed earth wall. This very same water is in equilibrium with water vapor in the surrounding environment. Due to this phenomenon, the wall becomes a proper naturel air conditioner and temperature regulator which enhances considerably the thermal comfort in the building. If the outside temperature is high, the water between the plates absorbs some of the heat from the room by evaporating. Similarly, if the outside temperature is lower than the wall temperature, the water between the plates condenses and releases heat. Thus, the earth uses the change of water state to transfer energy indefinitely.

- **Water resistance**

The water resistance of a material is linked to its ability not to absorb water. Water absorption test quantifies water resistance using a cube of earth immersed in 3mm of water. A comparative charts underlines the water resistance according different materials. [14] Other tests such as erosion test can underline the water resistance and more precisely its resistance to direct water exposition.

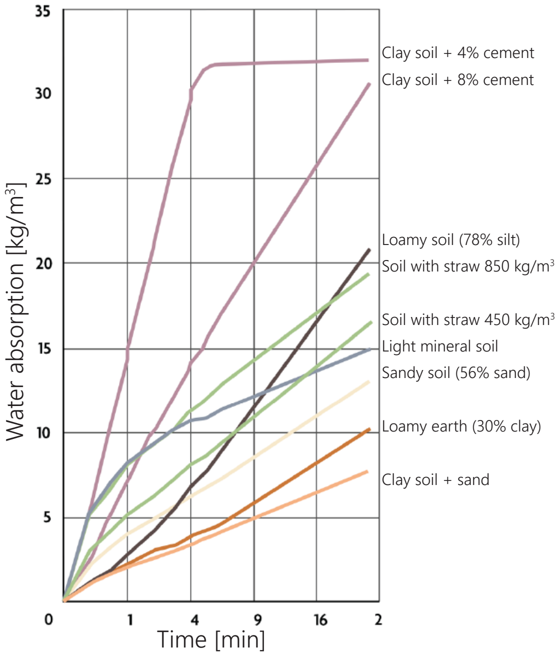


Fig. 3.8 - Comparative chart of water absorption test @C.Gnagne

1.d. Earth, a three-phase material

Raw earth is a three-phase material whose components interact with one another to define the whole system organisation and strength of the material.

The solid phase is composed of its mineral and granular elements made up mainly of pebbles, gravels, sand, silts and clay. Their proportions impact the composition as shown in fig 3.10. Due to the history of the creation of the earth as seen above, other organic components can be found such as live or dead plants, decomposing plants or animal matter, insects...

The liquid phase is due to water that according to its proportions determines the plasticity status of the material. (dry, humid, plastic, liquid...)

The gas phase is defined by the air included in the material. Indeed, its porosity can vary regarding the construction technique used and the compression of the material. Carbon dioxide, methane, nitrogen and oxygen are contained in the material.

These three phases must be present in the right proportions to obtain a good building material. The composition directly influences the physical and chemical properties of the material. The Carazas test, uses the three phases characteristic of earth to evaluate the best water proportion and the best compression needed for the construction technique wanted. [15]

Hence, to have an overall cohesion in raw earth, the clay proportion needed in the material is at least 10% of clay. However, over 40% of clay, raw earth is considered as clayey and thus too plastic and can't be used for construction. Furthermore, the organic matter content should not exceed 3%. For earth blocks an appropriate distribution would be 14% of clay, 22% of silt, 62% of sand and 2% of gravels. [7]

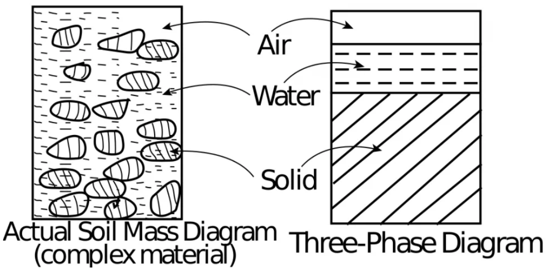


Fig. 3.9 - Three phase diagram of the soil @CivilArcho

1.e. Raw earth stabilisation

To improve the material proprieties and its resistance, different types of stabilisers can be used just like concrete. There are more than a hundred products that can be used to stabilise raw earth. However, stabilising a material must not be automatic. Indeed, it is often costly and complicates the material production. Thus the choice of the stabilsers depends on the type of soil used, on its quality and on the mechanical characteristics searched for. The question of environmental impact can also be raised as far as all stabilisers are not natural. Stabilisers can be used to make the material denser, to stiffen it by creating an anchor within it to reduce movement, to increase its resistance to water, etc. [16] The most used methods are : [17]

- **Mineral additions**

In case of an excessive clay content, minerals can be added such as sand or gravels to obtain a more evenly distributed soil composition and reduce the shrinkage during the drying process. Pozzolan or ashes can be used for the same reason. They also influence the compression resistance.

- **Cement**

The stabilisation with cement dates back to 1915. In order to have an efficient stabilisation, cement proportion are between 6 and 12 %. It directly impacts the material skeleton and creates different matrices within the material that work together to reinforce the material. It reduce shrinkage during the drying process, enhance the compressive strength, the tensile strength and the erosion resistance.

- **Lime**

This stabilisation with lime is more and more used in raw earth construction. Its proportion must be between 6 and 12% and depend on the type of raw earth used. It reduces shrinkage and swelling and enhances the compressive strength of the material and can even double it if the dosage is optimal.

- **Bitumen**

One of the main advantage of the bitumen is that it reduce the raw earth density and increases the optimum water and bitumen content. As other stabiliser, it reduces shrinkage, and enhances the compressive strength.

- **Natural fibres**

The use of natural fibres to stabilise raw earth materials is a widespread technique in the world. Among them, the most used are the straw fibres. Other fibres such as bamboo, wood, cotton, hemp and more can also be used and impact the material properties. First, they prevent shrinkage during the drying process. Moreover, they also distribute tension uniformly in the material. Then, they accelerate the drying process, by drawing moisture outwards through the fibres. Besides, they lighten the material and provide a better tensile strength. [18] Raw earth mixtures with natural fibres can be used in different techniques among which cob, wattle and daub, compressed earth bricks, and adobes. Depending on the proportion of fibres, the building material can be more or less lightened to fulfill its function.

2. PHYSICAL PROPERTIES OF RAW EARTH

Raw earth materials have been used for millennium already for their interesting physical properties. These properties vary depending on the nature of the earth, its composition, its quality and its construction technique. To state if a raw earth can be used as a building material, at least four basic soil properties have to be checked: cohesion, compressibility, granularity and plasticity of the soil.

2.a. Cohesion

Cohesion is defined as the attractive forces within a material that unify it and hold it together. For raw earth, the cohesion is due to three main cohesive forces : the capillary cohesion, created by water and its impact on clay layers, the electrical forces and the friction force, created by sand and gravels which give roughness to the earth. The material cohesion can be highlighted with the Carazas test which shows how water helps to a certain extent to create cohesion.

2.b. Compressibility

Compressibility is the capacity of a material to be compacted under static or dynamic compression reducing its volume. This aspect is also underlined by the Carazas test. Compacting raw earth material increases its compressive strength. In order to reach its maximum compaction, the water content must reach its "optimum water content" to enable each grain in the soil to be coated so that it can be rearranged into the densest pattern. It can be measured by the Proctor test

2.c. Granularity

The grain size distribution impacts the characteristics of earth. Indeed, each particles plays a role in the material and interacts with the others. The soil is classified according to the proportion of each type of particles (clay, lime, gravels, pebbles...) The effect of the particle size distribution on the hygromechanical properties of compacted earth may be as important as that of dry density or stabilisation.

2.d. Plasticity

Plasticity is the ability of a solid material to be submitted to deformation without elastic failure. For raw earth, plasticity also represents its capacity to be moulded and shaped; it confers to earth a great variety of shapes. Regarding the construction technique, the water content of the material is adapted to reach the required consistency (liquid, plastic, semisolid and solid). This change of consistency can be apprehended with the test Carazas and determined by the Atterberg test.

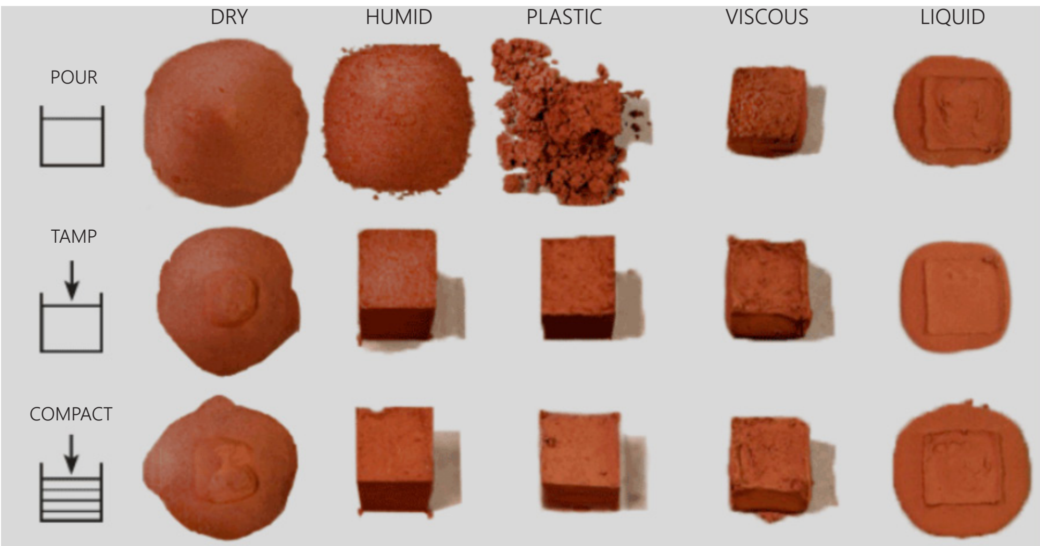


Fig. 3.10 - Test de Carazas @B.Cloquet for AMACO

3. TESTS TO CLASSIFY RAW EARTH

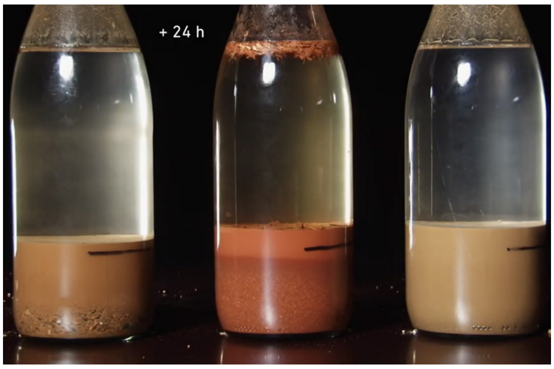


Fig. 3.12 - Bottle tests @AMACO

To identify the type of earth, classify it and state its different physical properties (colour, density, water content, porosity, looseness, structural stability, permeability...) two types of tests can be performed : field tests subjected to the tester's approval and scientific tests subject to more rigorous techniques and procedures.

3.a. Field tests

Name of the test	Description of the test	Aim of the test
Visual examination	Examinate the size and the colour of the soil	Identify roughly the soil granulometry
Touch test	Feel the size of the grains	Identify roughly the soil granulometry
Smell examination	Smell the earth sample to identify or not a musty smell	Identify organic materials presence
Hand washing test	If the hands are easily washable, it is a sandy soil otherwise it is a clayey soil. If it is slightly complicated the soil is silty.	Identify the nature of the soil (clayey soil, sandy soil, silty soil...)
Cigar test	A 20 cm long and 3 cm diameter cigar is created with raw earth material. it is gradually displaced into the vacuum and will break under its own weight. Its rupture length needs to be between 5 and 15 cm to be considered as usable for building purposes. Under 5cm, raw earth is not cohesive enough and above 15 cm, the material contains too much clay.	Identify the cohesion of the soil
Bottle test	Fill ¼ of a bottle with raw earth and the rest with water. Shake the mixture and let it set to observe the separation between the different components of the material.	Identify the particles proportion in the material

1. Sieving of the soil — *2. Creation of a plastic mixture* — *3. Creation of the cigar sample* — *4. Testing the cigar* — *5. Measurement of each sample*

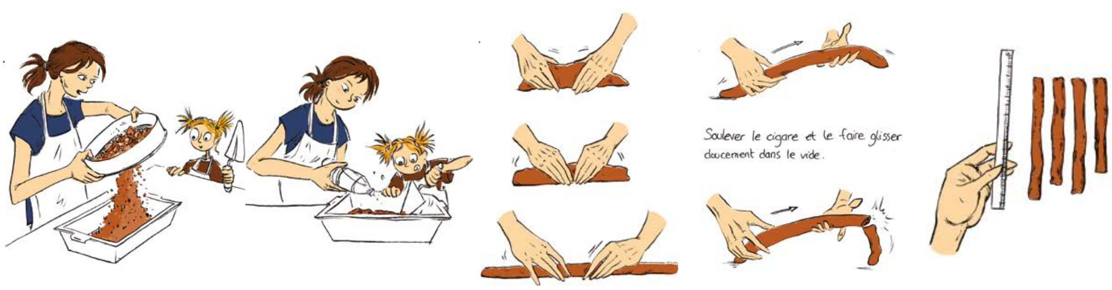


Fig. 3.11 - Cigar test steps @P. Sémont

3.b. Carazas Test

The Carazas test, named after the architect Wilfredo Carazas Aedo, explains how to turn raw earth into a building materials using the three phases involved. It was first used in 2001 for the DSA formation by CRAterre ENSAG to emphasize the correlation between the three phases of raw earth. It was then developed for 16 years in order to become a pedagogic tool to teach raw earth material and to build sustainable architecture.

A manual was then written by Wilfredo Carazas Aedo to continue the diffusion on a larger scale and to ensure the correct transmission of the experimental protocol and its objectives. The manual is intended not only for architects, constructors, engineers already using raw earth as a construction material but also archaeologists or other professionals working in buildings restorations for example. This tool is very interesting for the understanding of the different techniques in construction.

To make it accessible to all, this test is easy and feasible in realistic scale. The objectives of the tests are various. First it is to enhance people's knowledge of raw earth and understand the importance of the triphasic nature of earth material. Then it aims at developing a way to recognize the quality of land for building and identifying the best proportions of all material phases to reach its ideal properties. Indeed, the fact that water is often identified as a threat for raw earth construction underlines that proportions are crucial and participate in the transformation of raw earth as a construction material. Well dosed, water becomes the solvent and the cohesive agent for the granular components and influence the feasibility of constructive forms.

The test consists of a succession of combinations tests in which water content is variating regarding the solid components proportion. This will lead to different raw earth state : dry, humid or wet and plastic, solid, viscous or liquid.

The different samples are created mixing the soil and water dosed with a graduate bucket into a simple bucket. Then the mixture is either filled directly on a support, poured into wood mould of 15 x 15 x 15 cm or compressed. Then once it is dry, the samples are unmoulded, and placed in a matrix divided into 15 boxes, corresponding to each sample proportion. The aim is to create a visual matrix to emphasize the relation between the three phases.

Each sample will be correlated with a specific air and water proportion according to :
- The air component depending on the moulding of the sample : filled, pressed or compacted
- The water proportion influencing the final texture of the sample : dry, wet, plastic, viscous and liquid.

The results are obtained by visual interpretation of the appearance and shape. During the drying part, the operator also needs to check several times the samples and take notes on the way of drying, the appearance of cracks, the evolution of the shapes and colours, the position of the grains...

Fig. 3.13 - Humid soil sample compressed @AMACO

Fig. 3.14 - Carazas Test @AMACO

3.c. Granulometry test

In order to determine precisely the proportion of the different components of the soil, it is passed through several sieves with different mesh sizes. The granulometry test can determine the particles' size ranging from 0.075 mm to 100 mm. If grains are bigger than 100 mm, their catergorization will be done visually whereas for particles smaller than 0.075 mm, their categorizatoin will be done with Hydrometer Method. By noting the proportions passing through each sieve, the quantities of each soil constituent can be determined. A granulometric curve is also drawn to represent the mass percentage p of the different sieves as a function of the nominal opening size of the sieves. [19]

3.d. Atterberg limit

This test defines the limits of the consistency state of soil. Indeed, it determines the liquid limit and the plastic limit. Regarding the liquid limit, a sample of soil is spread in a small cup and divided in two by a groove of 4 cm long and 1 cm large. The recipient is dropped at height of 1 cm for several times until the groove closes on a length of 1 cm. The liquid limit is determined by the water content after 25 drops. Plastic limit is determined with another test consisting in remoulding a small sample of plastic soil by rolling it. The plastic limit is the water content at which the roll crumble. Knowing the liquid limit and the plastic limit, the plasticity index of the soil can be calculated. [17]

Fig. 3.15 - Granulometric composition test set @SDEC

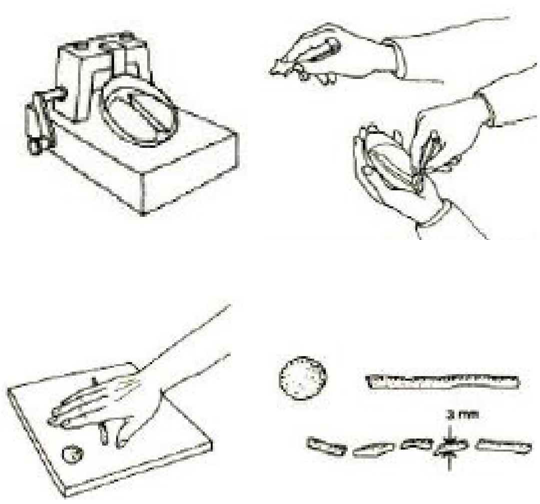


Fig. 3.17 - Atterberg limit test and Cassangre device @Guillaud & Houben

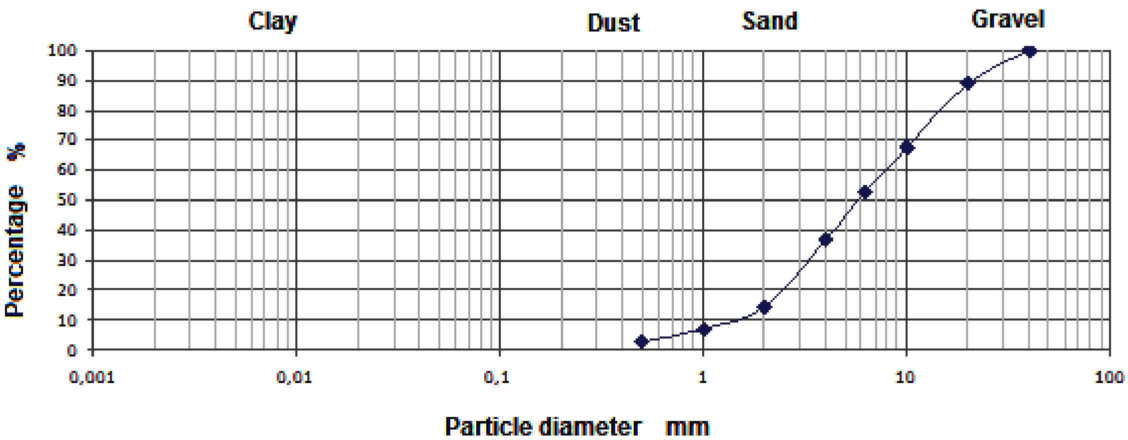


Fig. 3.16 - Granulometric curve @M.Lazăr

3.e. Proctor test

To determine the optimum water content, the Proctor test is performed. It consists in compacting a sample of the soil in a standard mould, following a standardized and well-defined process. Then the water content and dry density of each sample is determined after compaction.

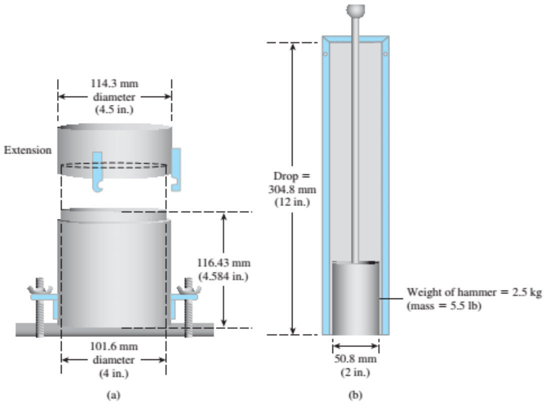


Fig. 3.18 - Standard Proctor test equipment : (a)mould (b)hammer @A. B. Salahudeen

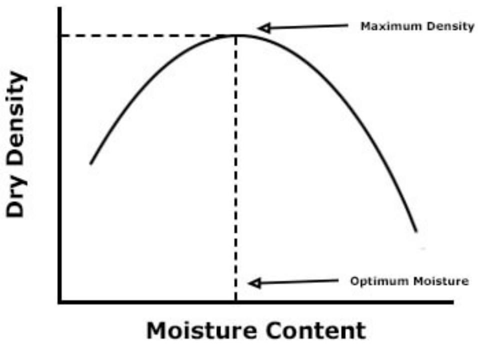


Fig. 3.19 - Proctor Curve @B. E.Backus

3.f. Compression test

A number of five samples are tested in a compressive machine. The samples need to have very plane and parallel surfaces for accurate results. An increasing force is applied on the sample until it reaches failure. During the test the vertical displacement of the sample can also be registered in order to draw the stress-strain curve. Taking in consideration all samples' compressive strength, the average compressive strength is calculated. In order to calculate then the characteristic compressive strength, used in structural analysis, a minimum of 100 samples need to be tested.

Fig. 3.20 - Compression test

3.g. Bending test

To evaluate the bending resistance of a material, a punctual load of 250 kg/min is applied at the centre of a sample. The load at failure is used to calculate the failure modulus of the samples. Taking in consideration all samples' tensile strength, the average tensile strength is calculated. As for compression test, to calculate the characteristic tensile strength value of the material as accurate as possible, a minimum of 100 samples need to be tested.

3.h. Erosion test

This test is performed to determine the resistance and the durability of bio-based bricks when subjected to rainwater. The test consists in dripping water in a regular way on brick sample to calculate the depth of the erosion caused and the penetration of humidity in the sample. To do so, a water regulation system is created with a flexible tube and a 100 mL graduate bucket. It will enable to dispense 100 mL of water on a period of time between 20 to 60 min. The dripping starts at 250 mm height from the brick surface. The brick is positioned with an angle of 27°. [20]

4. ADVANTAGES AND LIMITS

4.a. Advantages

Using raw earth as a construction material presents many advantages. It is a sustainable building material as far as social, ecological and economical benefits are concerned.

- **Ecological aspect**

Regarding environment, raw earth is definitely participating in its regeneration by being natural and resilient. Knowing that the construction sector accounts for 30 % of the worldwide carbon emissions, using raw earth as a building material can significantly reduce energy consumption and carbon emissions over the lifetime of the building. Besides, it is abundantly available in the world. It is an eco-friendly material whose use emits little $C0_2$ for its production, construction process and end of life alike. Indeed, the life cycle of the material is flawless : materials can be produced directly on site from earthworks and foundations. This involves almost no transportation, very little water and energy required to transform the material. Once the materials are produced, they are dried by the sun and wind. Moreover, its reversibility makes it easier to repair and rework.

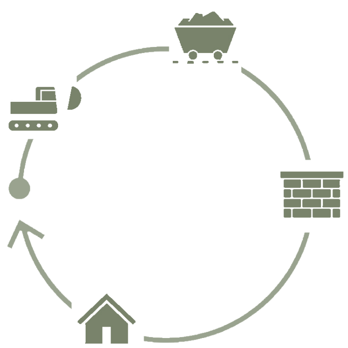


Fig. 3.21 - Life cycle of raw earth bricks

- **Economical aspect**

From an economic point of view, this material is also very interesting. Traditional production and construction processes are characterized by limited costs and minimum carbon footprint regarding industrial products. Even though, the labour can be more expensive it is balanced by the fact that it is a cheap material, that required low maintenance.

- **Social aspect**

It also presents advantages on a social level. First, it participates in reconnecting human to nature and culture. This material is also harmless for workers in comparison unlike other widespread building materials like concrete. Besides, building with raw earth also showcases the expertise, time and skills of the craftspeople, who act as resource people. Many raw earth projects are built with local participation or organised workcamp which enable more people to reconnect with nature in a way.

Fig. 3.22 - Community participation on a construction site @AMACO

- **Comfort aspect**

It also presents many advantages regarding comfort. First, being natural, the use of raw earth offers a healthy and pleasant indoor environment. Free from volatile organic compounds, it also offers sain working conditions for the workmen. Moreover, it has great performances : it has a nice acoustic regulation and a very good thermal inertia. It is a great hygrothermal and humidity regulator, essential for indoor comfort. This phenomenon is realised due to the presence of water in the material retained by clay particles. The earth uses the change of water state to transfer energy indefinitely and thus walls become proper natural air conditioner and temperature regulator. These performances are always linked to the environment especially in country with cold weather or hot weather that required well isolated buildings to avoid an over consumption of energy in cooling or heating. Finally, the uses of natural fibres improve the thermal and acoustic properties of the material.

Fig. 3.23 - Abetenim school in Ghana @A.Tabocchini

- **Aesthetic**

The plasticity of the material offers the possibility to confer to earth a great variety of shapes. For instance, some architects such as Anna Heringer play with this aspect to create informal spaces adapted to children. Besides, the different techniques can create different aesthetics. In the technique of rammed earth, the choice of different types of earth for the different layers can confer beautiful shades to buildings walls as seen in Fig. 3.23.

In conclusion, raw earth material responds to current societal issues, in particular for its ecological and sustainable qualities. It can significantly impacts the construction sector and reduce its important carbon emissions by cutting down energy consumption and carbon production over the whole lifetime of buildings. This is why the training of professionals in the sector is essential to be developed as well as the production sites of materials.

4.b. Limits

The use of raw earth in construction projects presents however drawbacks and limits.

- **Water resistance**

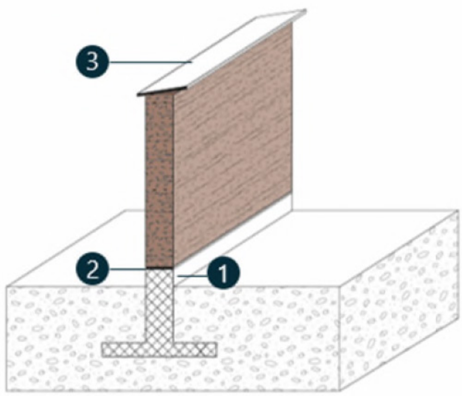
The water resistance of raw earth construction is poor. Indeed, walls must be well protect from the rain and from humidity during the construction process as well as during the whole life of the building

- **A poor social image**

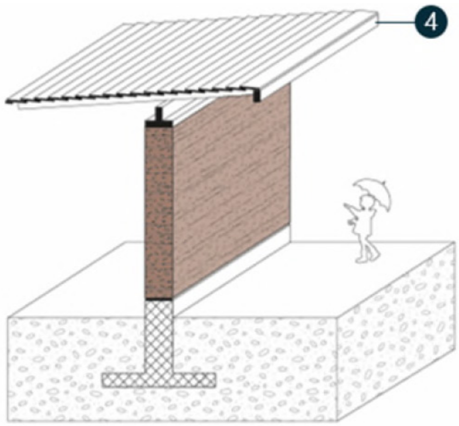
Nowadays, raw earth is often replaced by concrete, even in countries where this material is poorly adapted to the climate as in Senegal. This phenomenon dates back to colonisation and since then raw earth suffers from a poor image in social and technical terms.

- **Low recognition**

Raw earth material and its application techniques are not well documented and described in national standards. Because of this, contractors will favour the used of standardised material for insurance purposes. The situation tends to slowly evolve in some countries, but support from the governement is needed to speed up the process and offer accurate standards.



Protection of the wall during construction process



Protection of the wall throughout its life

Fig. 3.24 - Diagrams of means used to protect raw earth during construction and throughout its life @X. Davy and D. Puech at Egis Bâtiments Grand Ouest

5. BUILDINGS TECHNIQUES

The Earthen architectural heritage underlines the variety of construction techniques. These methods vary according to the location, the climate, the local materials and more. Each technique has its own specificities and requires a specific type of soil. There are about a hundred different techniques for building with raw earth. Among these, twelve main categories have been listed schematically by H. Guillaud and H.Houben.

5.a. Adobe

Producing adobes consists of shaping earthen bricks in a plastic state by hand or using moulds, then leaving them drying in the sun. To reach the plastic state the water content has to be between 15 to 30 %. Besides, fibres can be added to reduce shrinkage during drying. The adobes are then assembled using an earth mortar on a base made of water resistant materials to insulate the walls from damp. The bricks production is easy, fast and economical. The first traces of adobe date back to 8000 BC, and were found in Jericho and Mureybet.

Fig. 3.26 - Adobe production @F. Bekas

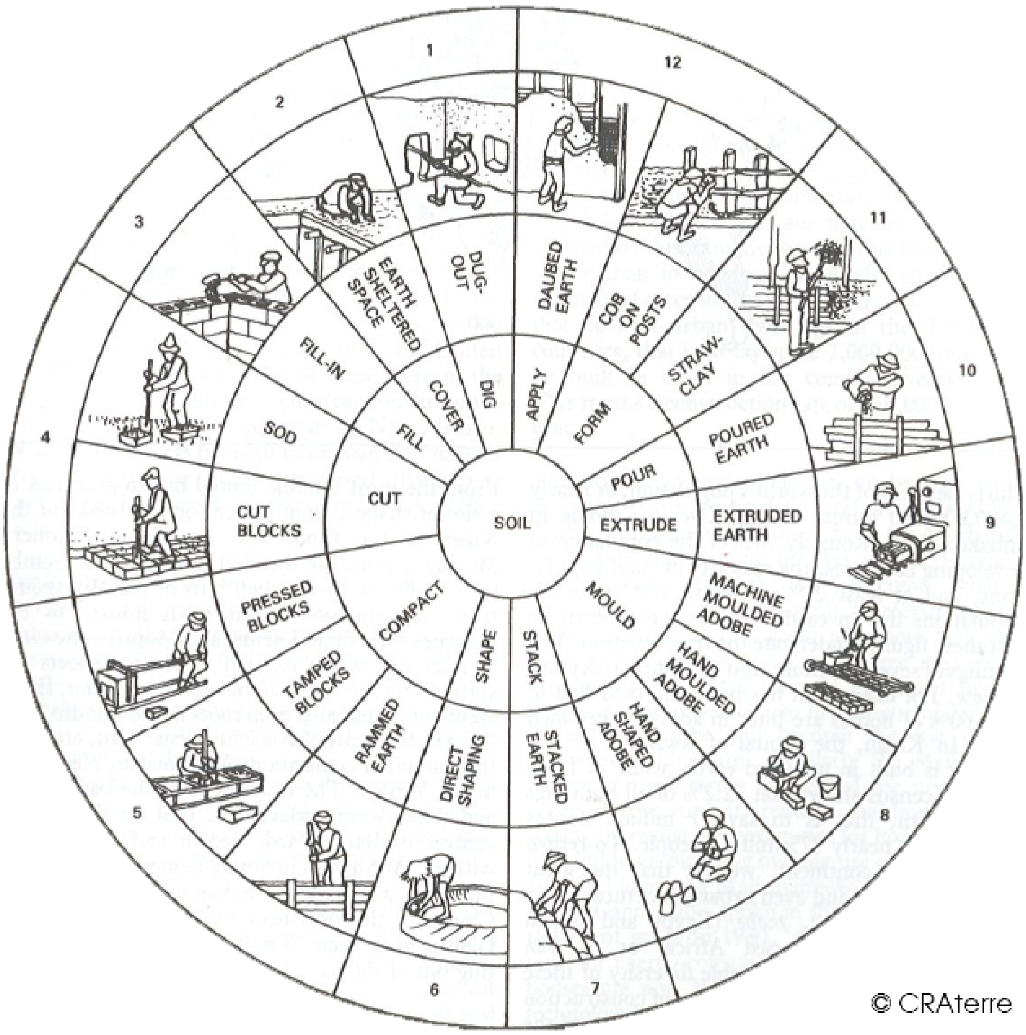


Fig. 3.25 - The wheel of techniques @Romain Anger & Leatitia Fontaine by CRAterre

5.b. Cob

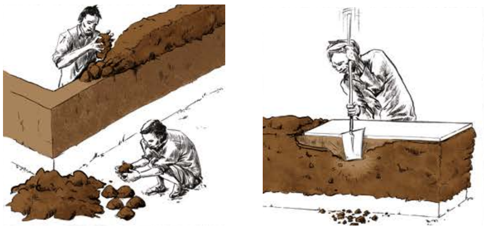


Fig. 3.27 - Cob technique @P. Sémont

Cob is a monolithic technique that consists in modelling walls with clay by piling up soil clods on a base. Vegetal fibres and minerals are often added to this mixture. It can be kneaded by animals such as buffalos. Each layer of earth is then beaten to close any shrinkage that may appear during the drying process. The walls are then trimmed, cleared of overhanging straw and plastered. Cob walls are between 40 cm and 60 cm thick. It is a robust technique that required few tools and enables a large variety of forms. However due to the minimum thickness required, the drying can be long (2 or 3 weeks). With wattle and daub, this technique is the oldest in earthen architecture and first appeared in the Near East in the Xth millennium BC. This technique is also very common on the African continent.

Fig. 3.28 - Cob construction @Twiza

5.c. Compressed earth bricks

Fig. 3.29 - CEB technique @P. Sémont

Compressed earth bricks (CEB) are manufactured using a mechanical or manual press. They can be stabilised with lime or cement if their mechanical properties need to be improved. Moreover, their production, based on the principle of compressing the material, gives them greater resistance to compression. They are dried in the sun for around 28 days before being assembled on a waterproof base using an earth mortar. The earth mixture must be homogenous, moist and powdery. Hence, the earth is first sieved before being mixed and placed in the press. It is a robust techniques that creates precise elements quickly. Besides, there is a possibility to prefabricate the CEB. However, the machine can represents a cost. CEB is a recent technique, dating back only to 1950 when the first manual press was created by the Colombian engineer Raul Ramirez.

Fig. 3.30 - Villa in Sindou in Senegal in CEB @Worofila

5.d. Rammed earth - Pisé

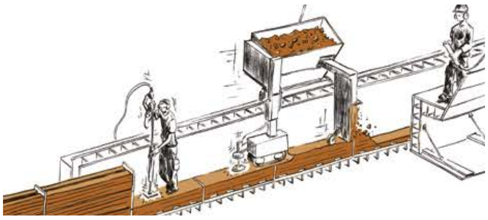


Fig. 3.31 - Rammed earth technique @P. Sémont

Rammed earth consists in piling up layers of 10 to 15 cm thick humid earth, each compacted in formworks by hand or with a tamping machine. Pisé walls are between 40 cm and 60 cm thick and formwork can be remove right after the tamping machine work. The earth layering creates a nice aesthetic. Besides, pisé wall can be prefabricated in order to reduce cost and timing on site. However, the cost of the machine and the lack of know-how can be a drawbacks for this technique. Rammed earth technique dates back to the IX th century BC in Carthage in Tunisia. Many pisé building can be found in the UNESCO architectural heristage, among them the great wall of china or Alhambra in Grenada.

Fig. 3.32 - Nk'Mip Desert Cultural Centre @N. Lehoux

5.e. Wattle and daub

Fig. 3.33 - Cob technique @P. Sémont

Wattle and daub consists of filling by hand a load-bearing wooden structure with light earth in a plastic state with no large grains. Marcelo Cortes applied this technique using a metal structure. To remain standing and prevent sinking, the mix must not be too clayey. Having the right proportion of clay also prevents from cracking as it dries. Plant fibres such as straw can be added to the mix to prevent these issues. The earth is then smoothed by hand, and the walls are checked for evenness using a wide spatula. This technique is easy to implement and only require few tools. With cob, this technique is the oldest in earthen architecture and appeared in the Xth millennium BC.

Fig. 3.34 - Wattle and daub @R. Waddington

5.f. Cut-out-blocks

The cut blocks are extracted from quarries and require tools such as pickaxes, saws, etc. The material must be hard in order to extract blocks. These blocks are then used to build walls or foundations.

Fig. 3.35 - Cut-out blocks @Article-25

5.g. Poured earth

Poured earth technique consists in pouring a liquid earth into formworks. Although this facilitates the implementation of the materials, it has a big drawback : its shrinkage during the drying process is very important. However, by stabilizing the material, this issue can be tackled. This technique requires more complex tools than the techniques presented above namely large formworks and a machine for pouring earth.

Fig. 3.36 - Poured earth wall @AMACO

6. MORTARS

6.a. Raw earth mortar

Raw earth can also be used as a mortar. Three layers composed a mortar namely, an adhesion layer, a body layer and a finishing layer. The earth mortar is made of fine earth composed of clay, sand to decrease the shrinkage and sometimes fibres and stabilizers. The adhesion layer is set on a rough and plane surface in a wrinkled way to enhance its grip on the other layers. To reinforce the mortar, a synthetic net can be added to the body layer. Finally, the finishing layer is made with a thinner sand and can be stabilized with lime in order to enhance its resistance to water.

6.b. Lime mortar

Lime mortar is composed of lime obtained by firing limestone, rehydrated slaked lime, sand and water. It is more resistant than the earth mortar and is waterproof. Besides, it has a lighter colour. Regarding its setting, the surface needs also to be plane but less rough as lime reacts chemically with earth. Protection are needed to apply lime mortar.

Fig. 3.37 - City of Shibam, Yemen @Tan Yilmaz

7. A CLOSER LOOK ON BIO-BRICKS

7.a. Definition

According to the Legifrance decree on the content of conditions for awarding the «bio-sourced building» label (2012), bio-bricks are : "material resulting from plant or animal biomass that can be used as a raw material in construction and decoration products, fixed furniture and as a construction material in a building". Biomasses are renewable resources that can be regenerated on a short period of time. Biobased material can be divided into five categories namely : [22]

- Forest products (wood, bamboo)
- Plants for green roofs, green facades...
- Plants fibres to reinforce composite materials (linen, cotton, elephant grass, bamboo, straw...)
- Plants aggregates coming from wastes and used in Bio-concrete, Bio-cement mortar, Bio-earth mortar
- Bio-SCM consisting in high performance concrete

7.b. Advantages

Bio-based materials present many advantages to be used as a construction material. First of all adding fibres to raw earth bricks have an environmental impact on the construction reducing its carbon footprint. Indeed, the fibres added are biodegradable and store CO_2. There are also a long lasting material if well maintained and their production is easy and economical.
Furthermore, adding vegetal fibres to raw earth enhances its thermal properties and the material ductility.

Besides, another important advantages of the fibres is its capacity to modify and enhance the mechanical properties of the raw earth building material. First, it can reduce shrinkage with a bridging effect during the drying process. In contact with a fibre, the propagating crack will either be retained by the fibres holding together the soil particles or will deviate from it forming macro cracks. Thus, the energy transported by the propagating flaw will diminish and have less impact on the material. However, the length of the fibres impact the shrinkage of the material. [12] Regarding compressive and tensile strength, it also increases the material resistance until a certain amount of fibres. Shear and flexural strengths are also enhanced by vegetal fibres. [23] [24]

Fig. 3.38 - Straw bio-bricks @EconoEcolo


@Francois Goudier

IV. GUIDELINES & OBJECTIVES

IV. GUIDELINES AND OBJECTIVES

1. Competition 85

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1. Competition framework

1.a. Balouo Salo

HUMANITARIAN ORGANIZATION
BALOUO SALO

Fig. 4.1 - Organization logo @Balouo Salo

Our architectural project was inspired and made part of the 2023 Kaira Looro Architecture Competition. This competition is organized by a non-profit humanitarian organization called Balouo Salo which aims at building infrastructure in the Casamance region and particularly in Tanaff and Baghere. Founded in 2013 by Raoul Vecchio and Jali Diabate, this non-profit association aims at improving the living conditions of the neediest communities in the Tanaff region. To achieve this, they put their aspirations and their knowledge in architecture to work for the benefit of others and tackle important issues. They built diverse noticeable projects which helped the community access to potable water, improve their health care system and the school system...

For example, 40-m-deep solar wells were built in Baghere, in Moyafara, in Kenwal in Talicourtou, in Sanoufly, in Sambacounda... and another one is about to be built in Tankanto. Regarding accessibility to water, other projects such as installation of catch basins in Tanaff High school were conceived.

Fig. 4.2 - Deep solar well in Moyafara @Balouo Salo

Fig. 4.3 - Deep solar well in Talicourtou @Balouo Salo

Regarding architecture, different projects have been conceived such as the cultural center of Tanaff, or the renovation of the school of Walicounda. Other projects will be soon realized such as the women's training center in Baghere to foster women empowerment and develop educational and entrepreneurial activities.

Fig. 4.4 - Work in progress for the cultural center in Tanaff @Balouo Salo

Regarding health, they carry out diverse types of projects such as a healthcare center to tackle child malnutrition. They also help the community with medical donation such as ultrasound echography equipment. Finally, they also offer conferences, conventions, seminars, courses, workshops... to raise awareness and share knowledge in the different communities.[1]

Fig. 4.5 -Raoul Vecchio and the workers @Balouo Salo

1.b. Kaira Looro

kaira looro
international workshop
architecture for Senegal

Fig. 4.6 - Logo of the competition @Kaira Looro

To develop projects, Balouo Salo launched Kaira Looro, an architectural competition with renowned architects, such as Kengo Kuma, Agostino Ghirardelli (SBGA), Benedetta Tagliabue (EMBT), Manuel Aires Mateus, Mario Cucinella, Raul Pantaleo... The competition takes place every year and is asking teams of designers to imagine a public building for a village in Casamance. The jury is composed of renowned architects and the winning project is to be built in Senegal by Balouo Salo. The framework is therefore limited by the means and objectives of the organisation.

The subject of the 2023 competition was a primary school in any rural area of Casamance. The pitch to the competition was described as following.

«The goal is to design a new school model that can protect and foster the development of every child's potential. A school that can raise the level of education for children, secure the right to study, ensure health and provide the psycho-physical and health conditions necessary to develop each student's potential. A facility that is not only limited to school courses, but that can host cross-curricular activities is ideal, a place that is not only a school but also a community.

Through architecture, shapes and colours, the aim is to create a model that inspires confidence in the students, the community and the authorities. A unique and symbolic, yet simple, place of identity in which every child can find themselves and begin to build their future.»

The competition also contained certain construction requirements, namely :

- be easily achievable through sustainable and self-constructing technologies, which therefore do not require the use of heavy vehicles and complex equipment;
- make use of natural and/or recycled materials, available in the area, so as to limit the economic-environmental impact and generate profitability in the area;
- be integrated into a rural setting

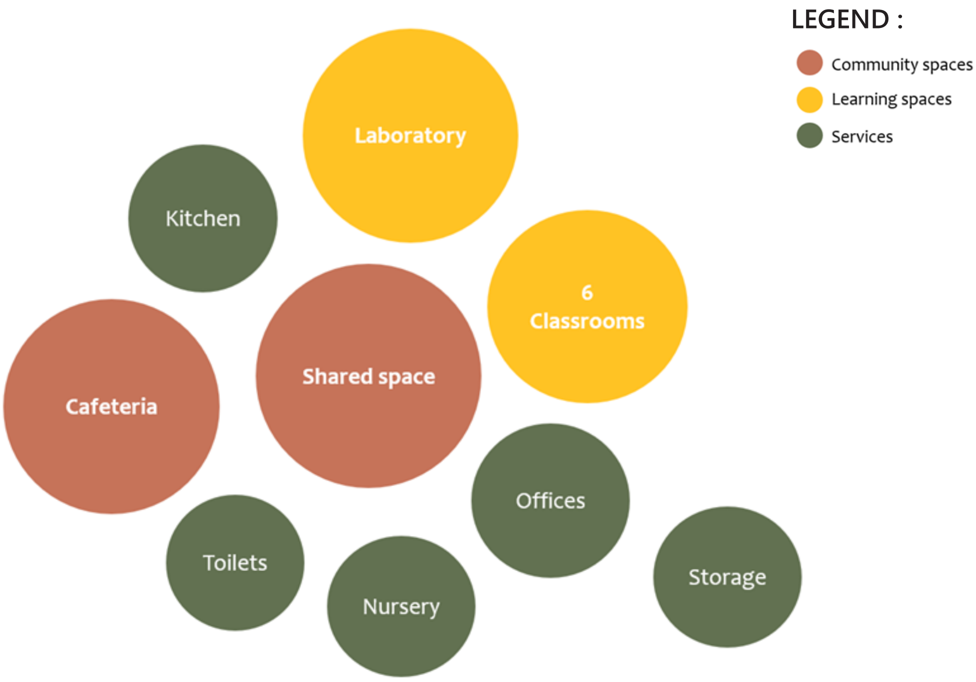

Fig. 4.7- Functionnal diagram of the competion requirements

The spaces required were listed as such :

1. Classrooms. There must be six classrooms with an average of 25 students each.

2. Offices. There should be offices for management, and a meeting room for the teaching staff.

3. Laboratory area. There should be a flexible space for organizing recreational activities and laboratories for the students.

4. Sickroom. There will be an environment for dealing with student injuries or illnesses.

5. Canteen. A space is to be set aside for the preparation and provision of meals for underprivileged students.

6. Storage. There should be a storage room for school materials and equipment.

7. Toilets. Facilities for students and school staff will have to be provided.

The design finally had to comply with the following characteristics:

- Maximum indoor area of 650 m2 for the previous areas;
- Ground floor only. Upper floors are therefore not permitted;
- The total cost of building materials alone (earth, concrete, wood,etc.) must not exceed €70,000;
- Give preference to the use of natural materials available in the surrounding areas, scrap and recycled materials;
- Promote sustainable and environmentally friendly construction technologies;
- Be easily self-constructed, with unskilled personnel and without the use of heavy vehicles.

During the design process, we kept all those objectives and limits in mind. We also wanted to go further by choosing a precise location in the village of Baghere and understanding the constraints and assets of this place. [2]

2. SWOT ANALYSIS

The SWOT analysis is a summary of all the characteristics of Baghere found during our context analysis, references remain the same. The Strengths and Weaknesses are the helpful and detrimental aspects of the local context on which our project can have an impact. The Opportunities and Threats, on the other hand, are unalterable aspects of the location that can have respectively a positive or negative impact on the school project. A big asset in the making of the SWOT was the testimony of Raoul Vecchio, president of Balouo Salo.

2.a. Strengths

To begin with, the analysis of the strengths was established in Tab. 4.1. First, the community is already strongly bonded, and some skills can be useful in building and teaching. Indeed, most of the population is farming and they could come together to provide food for the school cafeteria and teach agricultural skills to the children. Moreover, most houses are self-constructed, which means many villagers could give a helpful hand in the construction of the school. Some humanitarian associations are already present in the region and are helping fund and maintain the education system. We can imagine that these organisms could be of help in the construction and maintenance of the school.

Some facilities are already in use for the children and young people of Baghere. The Mosque is quite active and offers some religious classes. We can imagine some shared events and projects between the school and the Mosque. The football field of Baghere is being used extensively by the children. This place could be used by the school too, and sport can be a point of interest to introduce lessons to the children.

The terrain is flat in the area, which eliminates the need for any complicated terracing. The buildings and pathways must be thought out accordingly. The presence of trees around the site is an advantage as they can provide shading and reduce heat. They also help reduce damage in case of flood.

As mentioned earlier, the community's construction skills can be an advantage for the school. The villagers may also know techniques especially useful in this particular context.

SOCIAL	FACILITIES	ENVIRONMENT	CONSTRUCTION
Strong community spirit Agricultural skills Local partners for education UNICEF, PAM, PAEF-PLUS...	Active Mosque of Baghere Football field	Flat terrain Presence of trees around the site	Autoconstruction culture and skills

Tab. 4.1 - Strengths of the local context

2.b. Weaknesses

SOCIAL	FACILITIES	ENVIRONMENT	CONSTRUCTION
Struggling existing school system Poor hygiene Unequal food access High children mortality	Poor water system Unreliable electricity supply	Potentially dangerous fauna Proximity to a rather high circulation road	Generational loss of vernacular construction skills Limited tools and engines available

Tab. 4.2 - Weaknesses of the local context

The weaknesses of the local context are shown in Tab. 4.2. First, there is a preexisting school system in Baghere, which is struggling. Part of the difficulties comes from the buildings which were designed like many colonial schools, in cement with a metallic roof and no ceiling. They are not adapted to the climate and are falling apart. The schools also face a lack of teaching staff. The population also faces health problems due to a lack of hygiene and unequal access to healthy food. This is directly related to the water access problem; solutions could include rainwater collection. The school could also teach hygiene habits to children and parents alike. Some diseases can also be treated directly in the school nursery. The cafeteria could provide free healthy meals to children in need.

The poor water access in the region is a problem, people must go quite a long way for fresh drinkable water. The school could become a new water access. The electricity supply in the village is unreliable with low power and frequent power cuts. Therefore, the school will be designed in order not to rely on the electricity network.

The animals of the region can be dangerous and destroy cultures. An appropriate fence should be added to the school to protect children and fields. Moreover, the school is placed along the main road of Baghere which can concentrate a bit of traffic. A fence could also protect the children from the busy street. Offsetting the building from the street can also impact the school environment positively.

Progressively as traditional buildings are being replaced with cement construction, the vernacular construction skills are lost on the younger generations. The construction of the school can be an opportunity to teach younger people back those important skills. Moreover, the conservation state of many cement constructions highlights the fact that these type of constructions are not adapted to the local climate. Tools and engines are not easy to find in the region and the building shouldn’t require the use of engines or complicated tools.

2.c. Opportunities

SOCIAL	FACILITIES	ENVIRONMENT	CONSTRUCTION
Young population High enrolment in primary school Growing inclusivity in society Existing projects and programs for the youth	Water access through the drilling Growing internet access	Proximity to the river Arable land Ecosystem services	Local materials : raw earth, wood, vegetal fibers (rice, straw) No specific rules regarding construction restrictions

Tab. 4.3 - Opportunities of the local context

The population in Baghere is rather young with a lot of children and teenagers, which is an opportunity for the school. Moreover, the rate of enrolment in primary school in the region of Sedhiou is more than 100%. This means that school should be attended by most children without much need for campaigns. The society is also evolving to evermore include girls and women in school and jobs. There are already some projects and programs for the youth in Baghere and Tanaff, sport associations for example are active. This means that young people are already organized and motivated in coming together. These associations could benefit from the premises of the school.

There is a water access in Baghere which provides drinkable water to the village. This is an asset for health and could be used also for the cafeteria of the school. In addition internet access is spreading rapidly in rural areas of Senegal, with a growing number of people owning a mobile phone. This is a huge opportunity for teaching as teachers and students alike can gain access to the latest information for a modest cost. Mobile phones can become an interesting learning tool.

Fig. 4.8 - Baghere well @Balouo Salo

The proximity to the river makes the land more fertile. It also reduces the heat, and allows vegetation to grow, which can become a resource. The land is arable which means that people should be able to grow food inside of the school. The rich local ecosystems provides different ecosystem services such as the provision of food and fresh water, raw materials or climate regulation.

For the construction, the local assets are the presence of many quality materials. We can quote raw earth, wood and vegetal fibers coming from the local rice and wheat fields. These materials are available locally and degrade naturally with little to no impact on the environment. They also have great qualities in terms of thermal insulation and humidity regulation. The legal framework regarding construction is very permissive leaving room for innovation and creativity.

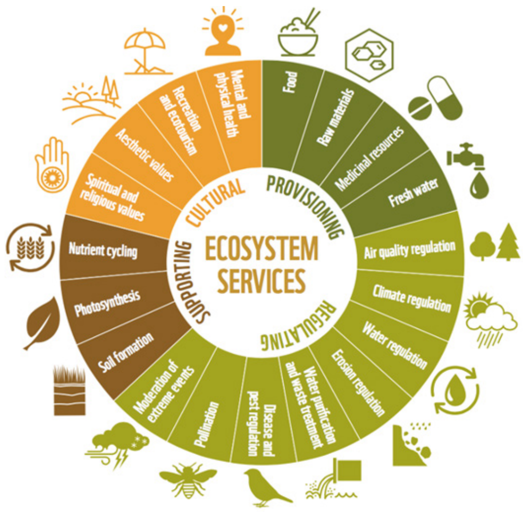

Fig. 4.9 - Range of ecosystem service provided by nature to humans @WWF

2.d. Threats

SOCIAL	FACILITIES	ENVIRONMENT	CONSTRUCTION
Control of the Islamic hierarchy Cultural bias against girls' education Lack and underqualification of teaching staff Poverty Lack of job opportunities	Remoteness from bigger cities Distance from higher education Bad Road quality	Important rainfalls Regular drought Extreme heat Occasional strong winds Climate change	Limited access to industrial materials

Tab. 4.4 - Threats of the local context

The village of Baghere is of religious importance. Therefore the Islamic hierarchy controls the decisions taken by the community. This can be a threat as they have been opposed to some cultural development in Baghere in the past making Tanaff the cultural centre instead. With Islamic mentality some bias against girls education may arise. Women are thought to have a different role of caring for the house and children rather than getting education. This bias is mostly seen in higher education, but it can be the role of primary school to inspire girls to keep on with their studies. The lack and underqualification of teaching staff is a worrying factor. The school should be made attractive for teachers, and help might be needed from other organizations. Poverty is also a characteristic that can hardly be influenced through this project. It can lead to malnourishment, diseases, and dropouts. Providing free meals can help children in need. Education and school supplies should also be provided for free when possible. The lack of job opportunities in the region is a problem because it gives little way out of poverty. As most opportunities are agricultural, children may drop out of school feeling like there is no purpose in studying. The school could teach agricultural skills too, so it may seem more useful to both parents and children. Some other programs could also be creating job opportunities in the region.

The bigger cities, that contain higher education facilities and better job opportunities, are far from Baghere. There is a middle and high school in Tanaff, but the postgraduate education is only available in Sedhiou across the Casamance river which no bridge crosses. Furthermore, the road are of bad quality and many people do not have motorized vehicles which makes travelling, long, difficult and expensive. The people of Baghere have little chance of getting higher education, or better-paid jobs.

The climate can be extreme in the region. The summer rainfalls are impressive, the temperatures are high and humidity levels too. Climate change already has observable consequences on agriculture such as decrease in crops, increase in pests and diseases. The consequences are also on the environment with increased risks of flooding and wildfire, salinization of the coasts and desertification. But it can also impact the people with an increase in malnutrition and higher transmission of diseases. The school should therefore have a minimal impact on the climate and ecosystem, and make itself a shelter from these extreme conditions.

Industrial materials can be hard to come across and expensive. The design should therefore be mindful of the availability of materials and their cost.

3. OUR OBJECTIVES

From the analysis of the environmental, educational, and social context, and in correlation with the objectives of the Kaira Looro competition and the Balouo Salo organization, we were able to define the following goals that were our main focus during the architectural design process.

- **Inspire confidence in students and empower girls in education through architecture**

The school should give children the will to come back to it, and the envy to study. It should be an inspiring space pushing them to continue their studies even after basic primary education. It could become a place to make children feel safe and strong and could become an escape from their everyday life that can be tough due to poverty, climate or social constructs.

- **Provide services for the wellbeing of all students and staff**

School can be a place where children learn hygiene practices that are sometimes lacking in this area. It can provide water access, sanitary toilets and basic healthcare treatments. Children can also receive a free healthy meal at school and learn about nutrition. The school can also be a learning place for parents, who can also get to know more about hygiene, healthcare, and food safety.

- **Make school a shelter from the harsh tropical climate**

The school should be adapted to the varying climate. The building can become an example of adaptation for buildings to come. Besides, it should provide adequate learning conditions by using passive adaptation strategies. It can also be a shelter for community gatherings during out-of-school hours.

- **Use local natural and recycled building materials to limit the environmental impact of construction**

The school should limit its impact on the environment which is already subject to worrying changes. Therefore, local natural and recycled materials will be preferred. The building should also use only passive strategies to avoid the need for air conditioning and electric lights. The building should be easily maintained to avoid the fate of the former school.

- **Involve the whole community in the building and maintenance of the school**

The community will be involved in the school. This can help convince parents to send their kids to school. The school will also benefit from the agricultural skill of the population through the presence of community-managed vegetable garden that will provide healthy food for the cafeteria. The community will also benefit from the infrastructure and be able to create projects and initiatives that will make it stronger.

Fig. 4.10 - Pupils going to school @Adobe stock


Lines of latitudes.
The major line of latitude marked
with 0° is called Equator.
And others are:
Tropical of Cancer 23½°N.
Northern hemisphere
Southern hemisphere.
Lines of longitudes.
the second largest
in the whole world
and longitudes
@Adobe stock

V. ARCHITECTURAL DESIGN

V. ARCHITECTURAL DESIGN

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1. REFERENCES

The analysis of the context and vernacular architecture helped us understand key principles in the implementation of a project in the Senegalese environment. The following case studies of contemporary projects of schools and centres for children in Senegal and around the world aimed at identifying the different construction techniques, the materials, the spatial organisation, and the sustainable strategies employed in high-quality school design. These enabled us to understand better the school's needs and its relationship with its environment in order to be implemented in the best way.

1.a. Fass School, Toshiko Mori, Senegal

Architect : Toshiko Mori
Year : 2019
Location : Fass, Senegal
Area built : 280 m²
Area covered : 520 m²

This school designed by Toshiko Mori is the first elementary school of the region, consisting of 110 villages, and can welcome up to 300 pupils from ages 5 to 10. [1] Inspired by the traditional hut of the Diola people of Casamance, it has been built with local and traditional skills and materials.

Fig. 5.1 - Fass school @Toshiko Mori Architect

- **Architectural organisation :**

The oval shape of the building and the thatch roof recalls the traditional impluvium of the Diola people and clearly gives a strong identity to the project. This renewed impluvium is perfectly adapted for a school as it creates a protected courtyard defined by the internal walls and facilitates the circulation between the four classrooms and two flexibles spaces arranged around the courtyard. Thus, the function of the impluvium remains the same, as it creates a protected interior space and collects water, but its shape has been modified. Indeed, the parametric roof has slopes with varying angle to create different heights, spaces and experiences inside the building. The re-imagined implivium roof gives a sensation of movement.

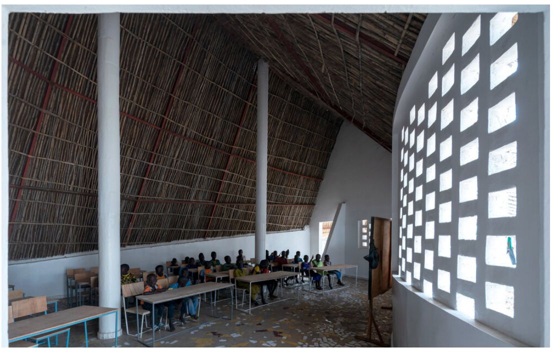


Fig. 5.2 - Openings @Toshiko Mori Architect

Another important aspect of the school is the alternation between closed rooms and open spaces around the courtyard. In particular, these open spaces are used as circulation areas but also as classrooms extension if needed with moveable partitions to have allow flexible use of the classrooms. This can be seen in the indoor plan of the school in Fig. 5.3 :

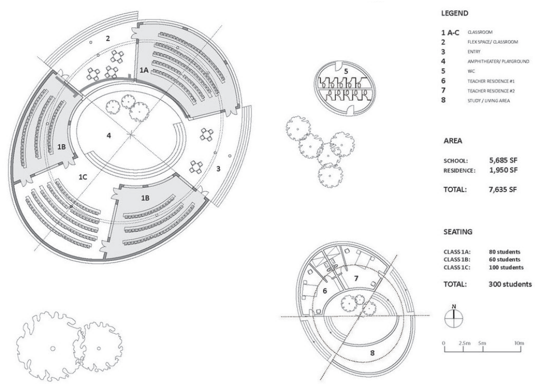


Fig. 5.3 - Fass school plan @Toshiko Mori Architect

- **Community involvement :**

The community was involved in every phase of the construction project. Instructions diagrams were given to the construction team to help with the sequencing of the structure's complex geometry. Their skills and knowledge were very important for the project realisation. Having a local team involved in the realisation of such a project not only enables an efficient construction process but also ensures appropriate maintenance on the long run.

- **Materials :**

Regarding the materials, walls are made of local mud bricks, painted in white to reduce heat and supported by small steel and bamboo members. Columns are made of reinforced concrete. The structure consists of structural walls and columns that also define spaces. They support a metal ridge beam. On these structural elements, spanning bamboo members are placed and carry the multiple layers of thatch.

- **Passive technologies :**

Finally, different techniques are used to ensure the comfort inside the building. Indeed, not only perforated walls ventilate and ensure a nice air flow throughout the building but also by vertue of the roof height, a stack effect allows hot air to rise to the top of the roof leaving cool air into the classrooms. The roof is detached from the walls to allow hot air to escape. Materials also play an important role for the comfort as the natural material used have a high thermal mass. Moreover, the water is collected by the roof and conducted in an existing aquifer. [2]

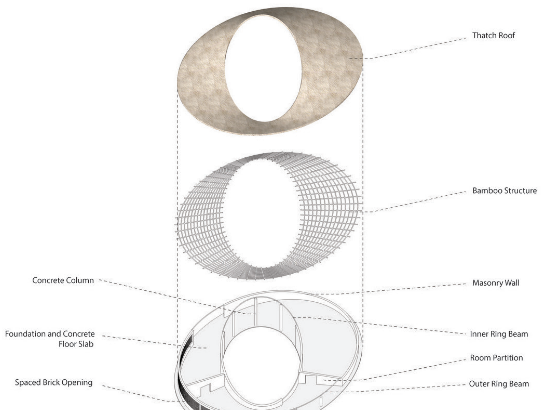


Fig. 5.4 - Material strategy @Toshiko Mori Architect

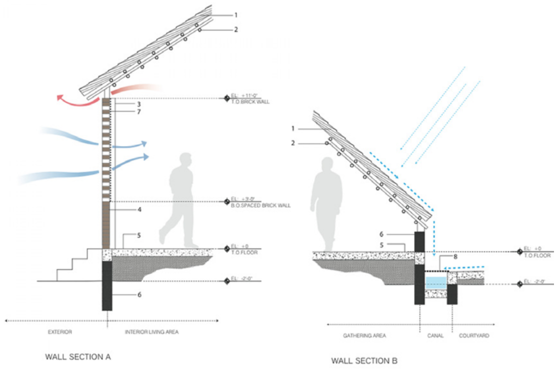


Fig. 5.5 - Passive strategies @Toshiko Mori Architect

Fig. 5.6 - Fass school under construction @Toshiko Mori Architect

1.b. Anandoloy centre, Anna Heringer, Bangladesh

Architects : Anna Heringer
Year : 2018 - 2021
Location : Dipshikha, Bangladesh
Area : 253 m^2

Located in Bangladesh, Anandoloy centre is a therapy centre for people with disabilities, as well as a textile workshop. In the local dialect, Anandaloy means “the place of profound joy” which echoes to all the lives that will be made safe, renewed, and empowered by this new therapy centre. The aim was not only to provide therapeutic treatment for disabled people but also to give them an access to learning and work.

Fig. 5.7 - Anadaloy center @K. Hoerbst

- **Architectural organisation :**

This two-floor building is characterized by its curved walls that are aimed at embodying and celebrating the differences in humanity. On the ground floor, offices, toilets, therapy rooms and classrooms are connected by an external porch that surrounds the building’s ground floor.

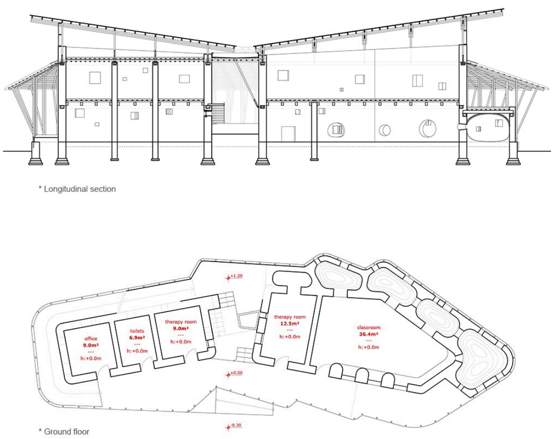


Fig. 5.8 - Section adnd plans @Stephano Mori

The classrooms are directly connected to snuggling rooms. These snuggling rooms are an interesting concept invented by Anna Heringer which consists of secret informal small spaces. These spaces are usually low, small and with organic curves. It fits perfectly for the younger pupils. It becomes their spaces, their hiding spot in which they can read, relax, play... On the first floor, office, toilets, therapy rooms and a nice workshop area are also connected with an external porch.

Fig. 5.9 - Classrooms with snuggling rooms entrances @K. Hoerbst

- **Community involvement :**

The biggest part of the budget was for the local workers. Indeed the main goal of Anna Heringer studio is to improve lives starting with the construction of the site in which the local knowledge is required. Thus, the centre became a life changer for the village as soon as its construction started. [3]

Fig. 5.10 - Construction in progress @S. Mori

- **Materials :**

Regarding materials, walls are made with cob mud. The roof in metal sheets and straw is supported by a bamboo structure. The upper parts of the roof made with metal sheet protects the building from rainwater, while the lower part in straw isolates the building. The external porch of the ground floor is protected by a thatch roof oriented towards the exterior. The long edged roof protects the raw earth walls from the rain. Some places have windows while others have openings in the walls to allow natural ventilation.

Once again, the natural ventilation and the use of natural materials with cooling properties are used to enhance the building's comfort. [4]

Fig. 5.11 - Mixing materials @S. Mori

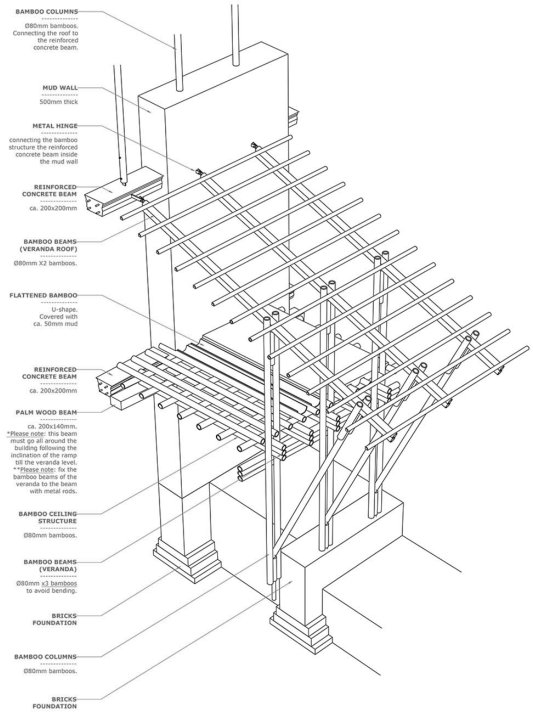


Fig. 5.12 - Construction details @S. Mori

Fig. 5.13 - Snuggling rooms @K. Hoerbst

1.c. Dano High School, Kere, Burkina Faso

Architects : Kere Architecture
Year : 2006 - 2007
Location : Dano, Burkina Faso
Area : 370 m²
Awards : 6th edition of the International Sustainable Architecture Prize, special mention
2008 - Global Award for Sustainable Architecture
2009 - BSI Swiss Architectural Award 201

- **Architectural organisation**

Located in Burkina Faso, this school composed of three classrooms, one computer room and one office is environmentally sustainable and adapted to local climatic conditions. Oriented towards the West, independent modules are arranged in a "L shape" under a single roof. Between the two blocks of modules, a shaded seating area below ground level has been created to host more informal lessons but also to be a social gathering place where people can meet, discuss and exchange.

Fig. 5.14 - Dano High School @E.J. Ouwerkerk

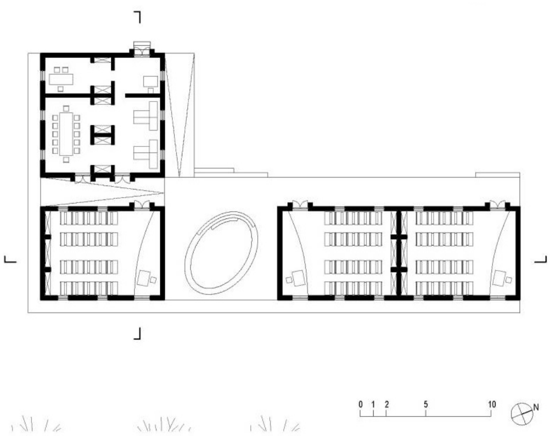


Fig. 5.15 - Dano High School @Kere Architecture

- **Community involvement :**

The construction was executed by local workers who had already participated in other similar construction sites with the foundation 'Schulbausteine für Gando" created by Kere. Not only are their local skills valued but the building methods that were taught to them have a social impact going beyond the construction process. [5] For example, the building durability can rely on their maintenance and their knowledge as far as they are the one who conceived it.

- **Materials**

Classrooms walls are mainly made of compressed eath bricks and a concrete chassis with continuous beams covering all the perimetral earth walls. This chassis is needed to carry the ceiling made of upside-down plaster vaults. These vaults recall the local architecture but also enable the air to flow throughout the classrooms. The ceiling is protected by a corrugated steel roof fixed on a steel structure attached to the ceiling. The long edge roof protects the crumbly clay walls from the rain and evacuates the rain towards the exterior owint to its unique slope. No glass windows are used but adjustable louvers to ventilate the buildings and control daylight inside the room. Made of two panels, they can be folded in order to manage air flow and light in the classrooms.

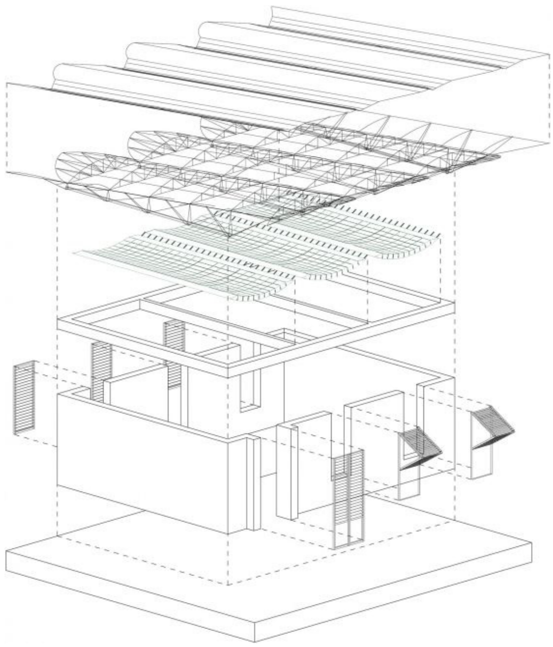


Fig. 5.16 - Classroom exploded view @Kere Architecture

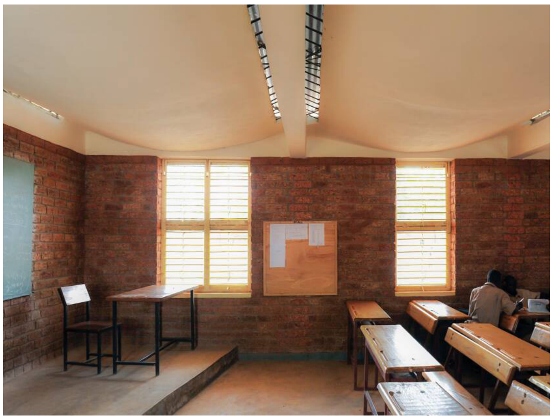


Fig. 5.17 -Classrooms @E.J. Ouwerkerk

- **Passive technologies**

In this project, Kere optimized the natural ventilation to have an important air flow in the building. Indeed, the double envelope roof evacuates an important part of the direct heat coming from the Sun, the openings create a nice air flow in the building and finally, the ceiling not only favours air movement but it also creates a stack effect due to its openings that allowhot air to rise to the top leaving cool air into the classrooms. Moreover, the orientation of the building to limit direct sunrays and materials also plays an important role for the comfort, and the natural materials used have a high thermal mass. [6]

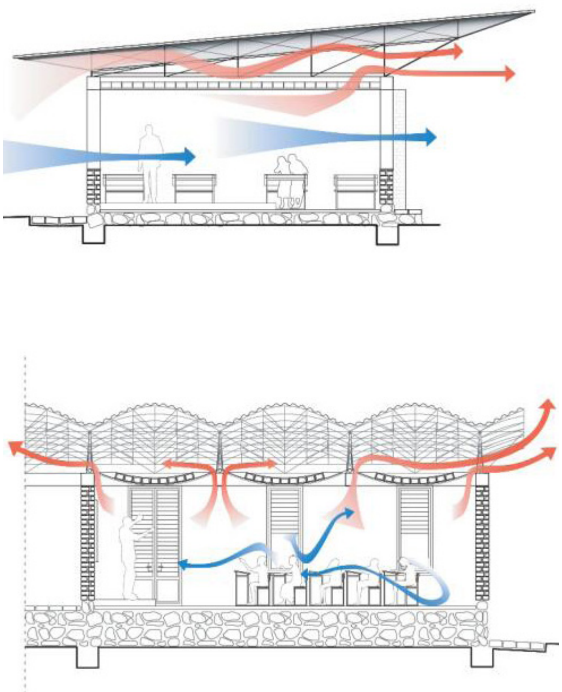


Fig. 5.18 - Natural ventilation diagram @Kere Architecture

1.d. Kamanar School, Dawoffice, Senegal

Architects : Dawoffice, David Garcia, Aina Tugores
Year : 2021
Location : Thionk Essyl, Senegal
Area : 1900 m^2

Located in Senegal, this school can serve up to 500 pupils. It was built as a response to the only overcrowed secondary school in the area of Thionck Essyl.

Fig. 5.19 - Kamanar school @N. de la Peña

- **Architectural organisation :**

Every classroom is an independent module arranged into a grid as shown in Fig. 4.21. The modules are staggered from one another to favour ventilation throughout the school. Somemodules are grouped together to create larger spaces. This adaptative system enables the school to grow over time if necessary by adding modules into the grid. The classrooms are all oriented towards the East and were projected around the existing trees. [7]

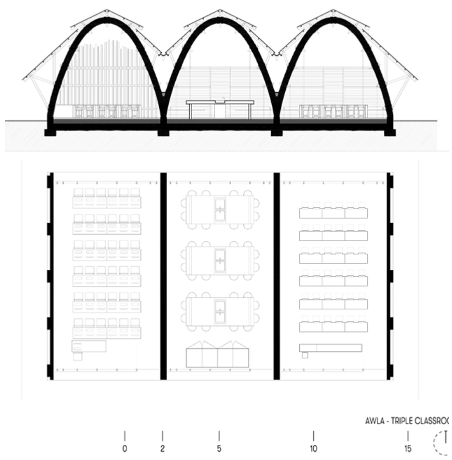


Fig. 5.20 - Sections and plans of classes @Dawoffice

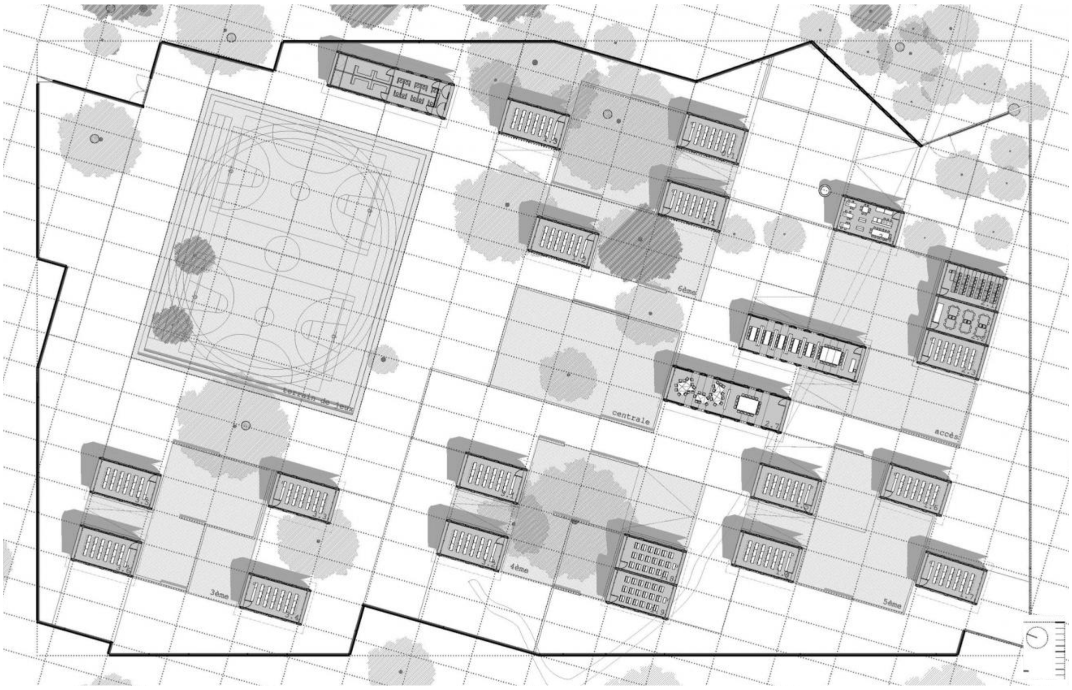


Fig. 5.21 - Kamanar school plans @Dawoffice

- **Community involvement :**

The construction was managed by the non-profit foundation Foundawtion and executed by 164 local workers, volunteers and architects hosted by local families. Their involvement goes beyond the construction process as they benefit a lot from it : the remuneration and the acquisition of tools directly impacted and benefited the households. [8]

- **Materials :**

The architecture is harmonious and uses vernacular techniques. Indeed, the classrooms consist of Nubian vaults separated with vertical openings on the whole height of the building with wood louvers. The Vault is made with compressed earth blocks which are hand pressed, and composed of local clay, soil and 8% of cement. [9] They are protected from the rain with a double roof in corrugated metal sheets oriented towards the exterior of the modules.

Fig. 5.22 - Construction in progress @J.Valera

Fig. 5.23 - Library @Dawoffice

1.e. Maternity waiting village, Mass Design group

Architect : MASS Design Group
Year : 2015
Location : Kasungu Malawi
Area : 670 m²

In order to tackle the lack of maternal facilities in rural area and thus reduce life-threatening risks for pregnant women, this innovative maternal waiting home was designed by MASS Design Group. This building provides decent maternity facilities with skilled professionals, good sanitary systems and good living conditions notably by its efficient ventilation.

Fig. 5.24 - Maternity Wating village @I. Baane

- **Architectural organisation :**

Small modules are arranged informally around a courtyard to recalls the vernacular layout of Malawian villages. The spaces created by this organisation and the small housings give birth to social places where women can share experiences and encourage first time mothers. The modules are easily replicable so the village can be extended or exported and adapted to other sites in the country.

Fig. 5.25 - Satellite view @I. Baane

- **Materials :**

Each module is made with local compressed stabilized earth blocks walls. In order to carry the roof structure and avoid a possible roof lifting by the wind action, the structure is attached to a concrete chassis with continuous beams covering all the perimetral walls. Each module has a nice porch covered by overhanging roofs made of corrugated steel. The porch is made of earth columns and carries the roof wood structure. The roofs have two slopes sometimes inverted and a system to collect rain water and store it underground. Regarding openings, they vary depending on the place's function. Indeed for sanitary purposes, windows are used while housings modules have perforated walls.

Fig. 5.26 - Maternity Wating village @I. Baane

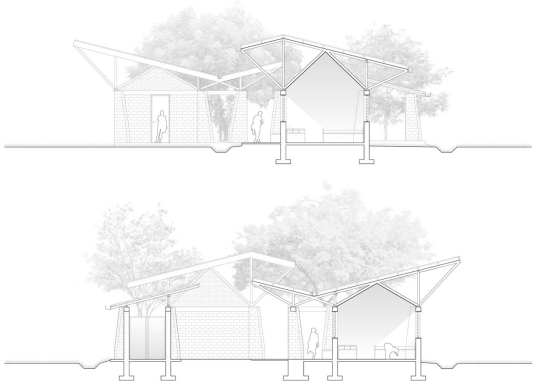


Fig. 5.27 - Sections @MASS Design Group

- **Passive strategies :**

Unlike many projects, electricity is used for different facilities of the maternity waiting village, for example, for medical furniture such as echography machines. Moreover, it is also used to ventilate medical blocks. [10]

Regarding passive strategies, good liveable conditions are provided with the perforated walls creating a good ventilation, combined with the overhanging roof shading area and earth-based material with high thermal capacities.

1.f. Schorge Highschool, Kere Architecture, Burkina Faso

Architect : Kere Architecture
Year : 2014 -2016
Location : Koudougou, Burkina Faso
Area : 1600 m²

Located in Burkina Faso, the Lycée Schorge Secondary School sets a new standard for educational excellence in the region. Its innovative and notorious design built with local building materials tackles current challenges such as education and ecology. Its main goal is to serve as a catalyst to inspire students, teaching staff and the local community. This noticeable architecture not only became a landmark in the area but is also the proof that local material and skills can create sustainable and lasting inspiring building.

- **Architectural organisation :**

Nine modules are gathered into two buildings and arranged in a semi-circle around a courtyard protected from exterior agents. Between the two buildings, transition spaces become places to socialize, rest... The classrooms are linked with an outside porch created by the long slopes of the roof ending in perimetral lattice. Indeed, the roof is a overhanging roof on both sides of the classrooms oriented toward the centre of the building. It is a double roof system with corrugated steel panels supported by a steel structure and a ceiling made of perforated plaster vaults. This double envelope roof favours natural ventilation and it is combined with a wind tower in each class. These arrangements give to this centred building a dynamic rhythm.

- **Materials :**

The walls are made from locally harvested laterite stone. They are extracted from the earth and hardened when under the sun. The furniture was made locally mainly with leftovers of the construction to reduce costs and wastes. Local craftsmen were involved in the construction process. There are no glass windows but panels that can be opened as louvres to ventilate the classrooms.

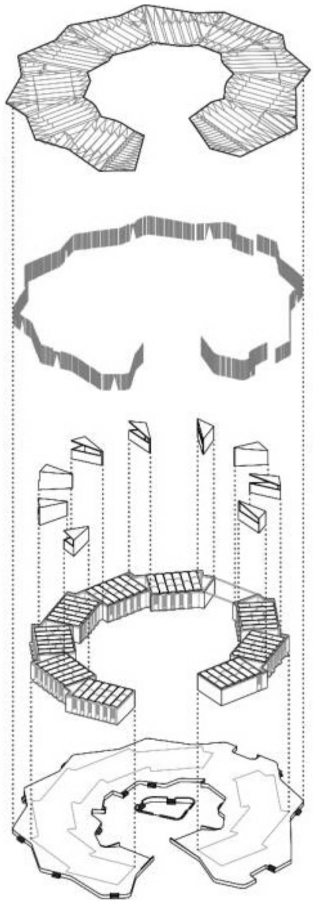


Fig. 5.29 - Exploded view @Kere Architecture

Fig. 5.28 - Schorge Highschool, a new landmark @I. Baan

Fig. 5.30 - Porche created by latteral wood lattice @A. Maretto

Fig. 5.31 - Classroom @A. Maretto

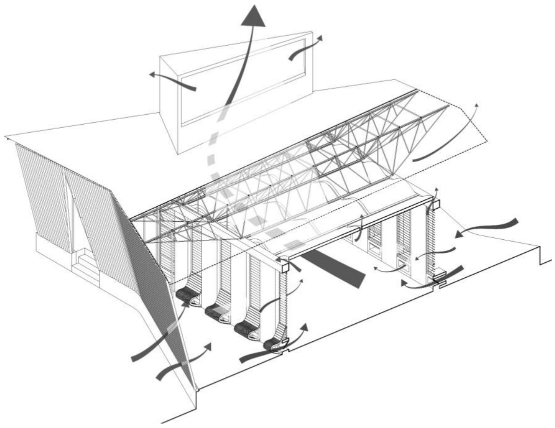


Fig. 5.32 - Passive strategies for natural ventilations @Kere Architecture

- **Passive strategies :**

Important passive strategies have been developed to ensure good study conditions inside the school. Indeed the combination of the double roof to avoid direct sunrays and heat in the classroom combined with solar chimney, overhanging roofs and material with a high thermal mass really enable to lower significantly the temperature of the classrooms. Moreover, the ventilation is also ensured by the slotted ceiling that expels hot air through its openings and louvres that also bring a certain amount of light into the classrooms. Finally the perimetral lattice and the overhanging roofs create a nice shade all day long for the pupils where they can wait to attend their class, discuss... The shaded spaces become social spaces. [11]

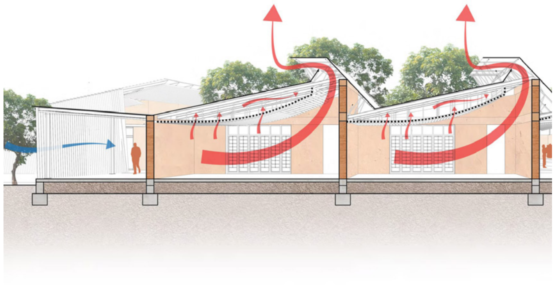


Fig. 5.33 - Passive strategies for natural ventilations @Kere Architecture

1.g. Dwabor kindergarten ARUP, Ghana

Architect : Arup Studio
Year : 2011
Location : Dwabor, Ghana
Area : 103 m²

In 2004, to tackle the issue of low enrolment in kindergarten in Ghana, the government has launched a development policy to increase support in the kindergarten sector. Indeed only 60% of children attend kindergarten. To reach their goals, estimations found that around 8000 kindergartens should be built and more than 3700 should be renovated. [12] Moreover, the environment in which they are built are usually rural areas, often in marginalised places and under a harsh tropical climate. Thus, not only do buildings need to be conceived to be adapted to the environment but they also have to be minimised as far as resources and energy consumption is concerned. In this context, The Sabre Charitable Trust education charity approached Arup studio to work on a kindergarten project to improve the education and thus the future of children in the marginalised area of Dwabor. The whole project was designed based on the local needs, materials, resources, culture, skills... The goal was to create a place that could be perfectly adapted to its environment but also connected with the community and with low environnmental impact.

Fig. 5.34 - Two classrooms @ARUP

- **Architectural organisation :**

The modular school is organised around a large circulation area. The two classrooms which are arranged along this core circulation area, interact and are completed with external teaching areas. These external teaching areas are protected from the sun with fabrics. Having shadowed places in such climate is very important. Not only are they used for teaching reasons, but they also become social spaces during playtime. Unlike many kindergartens in Ghana, the project also includes toilets, a kitchen and a staff room in the design. Moreover, it respects Unicef standards for 'child-friendly' schools. The arrangement of the functions aims at providing interaction and facilitate the monitoring of the pupils. Besides, two biodiversity planting areas have been implemented. They can be used for teaching purposes but also for the cafeteria and the community.

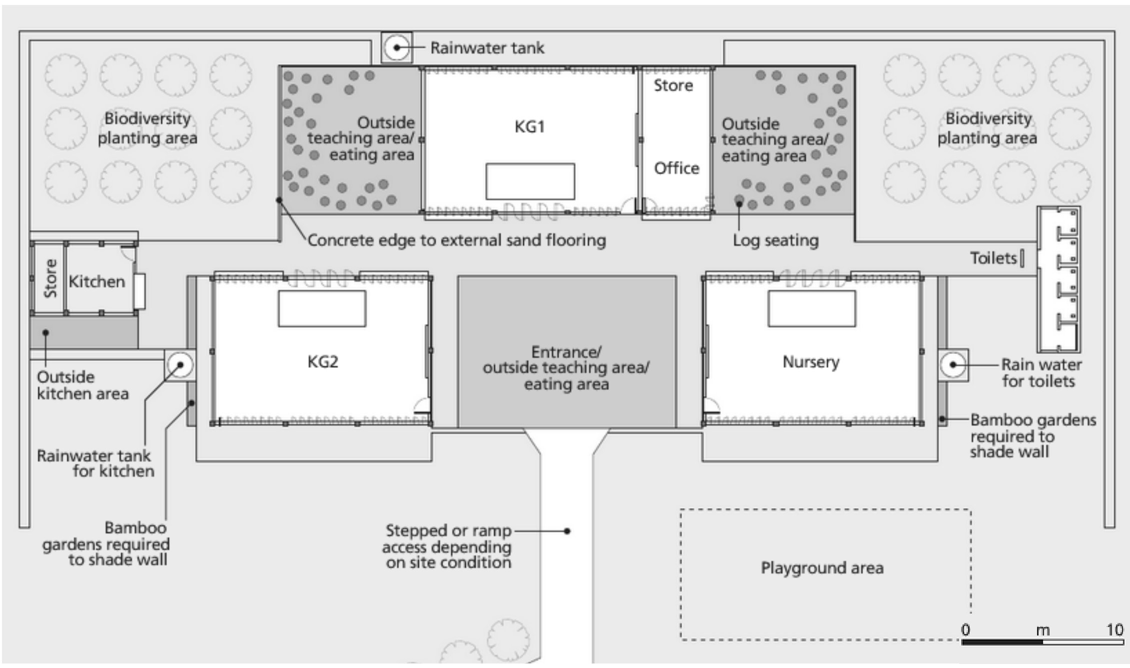


Fig. 5.35 - Plans and functions @ARUP

- **Community involvement :**

The construction was carried by local builders and included the whole community. Indeed, the community was always informed of the progress of the project, the daily timeline was managed by the elders for example, and all the documents (plans, sections...) were in free consultation. The process of construction encouraged the socio-economic growth of the community as the craftsmen would develop new skills that could be used for their future jobs. Non paid workers from the community also helped in the construction.

Fig. 5.36 - Daily timing consultation @ARUP

- **Materials :**

Natural and sustainable materials were mainly used for this project except for the structural concrete frame. Not only are they cost effective, but also the aim of their use is to demonstrate how natural material such as coconut husks, soil or bamboo can be transformed into sustainable building materials. Regarding the roof, corrugated metal sheet were used to collect rainwater. To cancel the rain noise and reduce direct radiation, coconut fibres were used as sound and heat isolation. The roof is supported by a wooden lattice

Fig. 5.37 - Coconut husks as isolation @ARUP

structure. The off-centred pith roof with long hanging slopes not only provides shaded area for the classrooms and their surroundings but also collects rainwater that is then used for cooking, hand washing.... The walls are made of mud bricks and completed with bamboo to clad the walls and ceilings. Finally, to manage air flow and light flows, moveable wooden louvers are used for windows and doors. [13]

Fig. 5.38 - Coconut husks as isolation @ARUP

- **Passive strategies :**

As the area is marginalised and the electricity hard to import and expensive, only passive strategies were introduced. All strategies were precisely studied to optimise comfort, starting with the use of natural resources. The rain water is collected and then used for the aforementionned above. Regarding the lighting, pivoting bamboo shutters were installed to regulate daylight and ensure an illuminance between 300 and 3000 lx in each classroom. As far as thermal comfort is concerned, the ventilation is guaranteed by a natural airflow. Indeed, owing to the north south position of the school aligned with the dominant wind and the bamboo wall lattice, the air can easily flow in the classrooms.

Fig. 5.39 - Passive strategies @ARUP

1.h. Econef Children's centre, Asante Architecture & Design, Lönnqvist & Vanamo Architects, Tanzania

Architects : Asante Architecture&Design,
Lönnqvist & Vanamo Architects
Year : 2018
Location : Kingori, Tanzania
Area : 650 m^2

This Children centre is aimed at improving the living conditions of the orphans in the Arusha area. It is composed of sleeping quarters and classrooms that can serve up to 25 children.

- **Architectural organisation :**

It is organised along a long corridor that serves rooms and courtyards located to create a nice centre protected by the surrounded buildings. Around the courtyards, porches covered by corrugated steel roofs offer different spaces for the children. Openings are made of louvres, glass windows or perforated walls. Besides, vegetables gardens were added and are used daily by the children and their teachers.

Fig. 5.40 - Plans @Asante

- **Community involvement :**

The construction was carried out with the collaboration of local builders using their knowledge and skills. The main materials are earth and wood. Indeed, the walls+ are made with local burnt bricks on which a concrete chassis with continuous beams covers all the perimetral walls and carries the roof structure.

- **Materials :**

Local clay bricks have been used for the structural walls combined with a concrete ring beam. This beam is used to maintain the mansonry in case of an earthquake. Clay bricks offer more mechanical restistance than raw earth bricks. The roof is supported by a wood structure and is detached from the ceiling to create a significant airflow between them and thus avoid direct sunrays and heat.

Fig. 5.41 - Construction in progress @Asante

- **Passive strategies :**

The construction was carried out with the collaboration of local builders using their knowledge and skills. This building implements sustainable design principles. Indeed not only is it a social place for kids, but it is also a sustainable economic and eco-friendly place. The centre produces its own energy through solar panels, collects and stores the rainwater in a trunk and ventilates the buildings with natural ventilation integrated in the architectural design . (perforated windows, scattering of the buildings, wooden lattice....) The water, stored in a 120 000 litres trunk is used to grow vegetable gardens and to supply laundry facilities, showers... [14]

Fig. 5.42 - Courtyard @Asante

1.i. References comparison

Comparing all the references, five important aspects for the buildings have come out.

- Durability :

It is the capacity of a building to withstand the test of time. This is linked to its materials, its building techniques and the way in which the environment and its different aspects have been taken into account in the architecture. Generally, with local materials, passive strategies, economic and social aspects, all projects were made to last even though some of them will have an easier maintenance than other. [15]

- Passive strategies :

They are all the strategies implemented to ensure comfort for the users and making buildings autonomous. For example, Econef Children's centre, Dano High School and Schorge High school implemented great passive strategies that give a great autonomy to the buildings and nice living conditions.

- Natural materials :

It refers to the proportion of natural materials. Indeed, some of them used more local materials such as Anandoloy Centre in comparison to the Econef Children's center.

- Vernacular architecture :

The similarities with vernacular architecture are taken into account to assess how well the building fits in with the local architecture. Many aspects of local architecture are found in the exposed projects, sometimes similar to the traditional way sometimes completely renewed, as in Fass school by Toshiko Mori architects.

- Local participation

Except from the architectural part, which is often taken care of by foreign studios and sometimes supported by charities, most projects are built by local workers and craftsmen. This aspect also takes into account, the benefits of all the construction process after the accomplishment of the work (new knowledge and skills, tools, wages...)

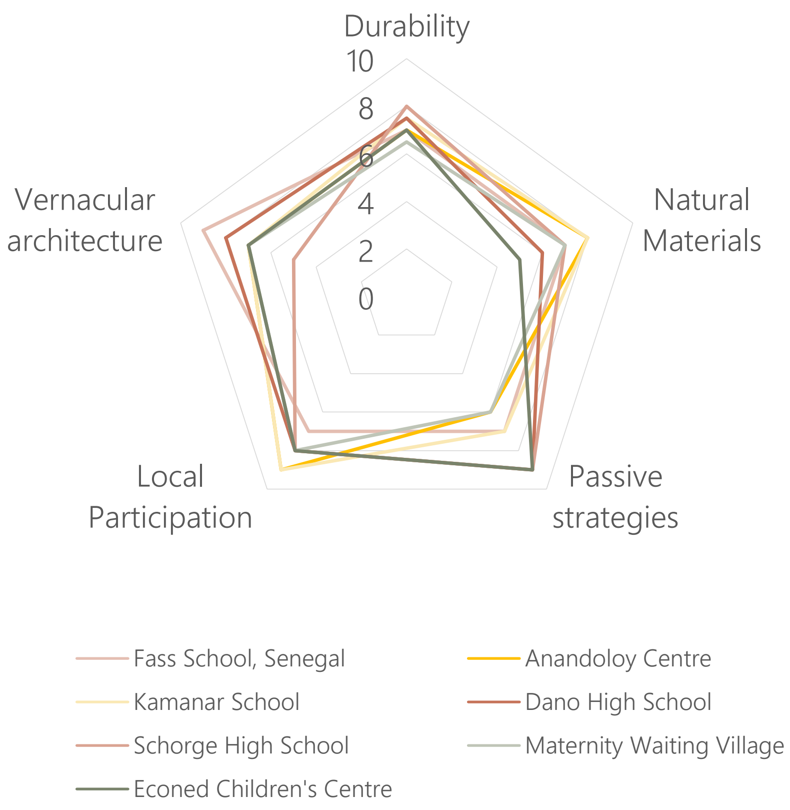


Fig. 5.43 - Comparison references diagram

2. CONCEPT

2.a. Governing principle

"It takes a village to raise a child".

This sentence often associated to African wisdom, reflects the importance of the community's dedication in the upbringing of children. Indeed, the African mindset is all about community and collaboration. Thus, a kid is not just raised by a single home but by the larger family involving older brothers and sisters, uncles, grandparents, cousins and even neighbours and friends. Thereby, every single person interacting with the child will in a way raise them and participate in the creation of a safe environment conducive to the child development.

Therefore, the projected school takes inspiration from the villages of Casamance. This reference has influenced the architectural design but also the relationships between the different functions inside of the school and between the school and the village itself. These relationships are intended to encourage the connections across ages and differences and the sharing knowledges, values, and experiences.

2.b. Functionality requests

To the list of functions required by the competition, we added other functions taken from studies and reference projects for further benefit to the children. The next step was defining the links that would connect them together.

In creating a school, designing internal spaces is crucial as it will host the main functions which are teaching, creating and eating. However, it is also very important to design external spaces that encourage social interaction, aligned with the local way of living.

We first identified the places that could be used by both the community outside of school hours. The cafeteria, the laboratory and the kitchen had to be close to the main entrance while the classrooms had to be placed away from the main road to avoid noise, distraction and disturbance. Placed in the centre the courtyard was perfectly located to be the link between these two important "blocks". To enable their access, the toilets and the offices are arranged around the courtyard and near the classrooms.

Then, we thoughtout the external spaces and their connections with internal ones. It was quite clear to link the outside learning space to the classroom, the terrace to the cafeteria and the outside auditorium as an extension to the laboratory. The piazza, accessible daily by the parents, was placed at the entrance.

Moreover, the storage room and the reception are the two functions which are not connected directly to the courtyard but to the offices for the storage room and to the main entrance for the reception.

Finally, the vegetable gardens were placed near the classrooms so they can have teaching purposes. They are also placed in order to be easily accessible by the community from the courtyard if needed.

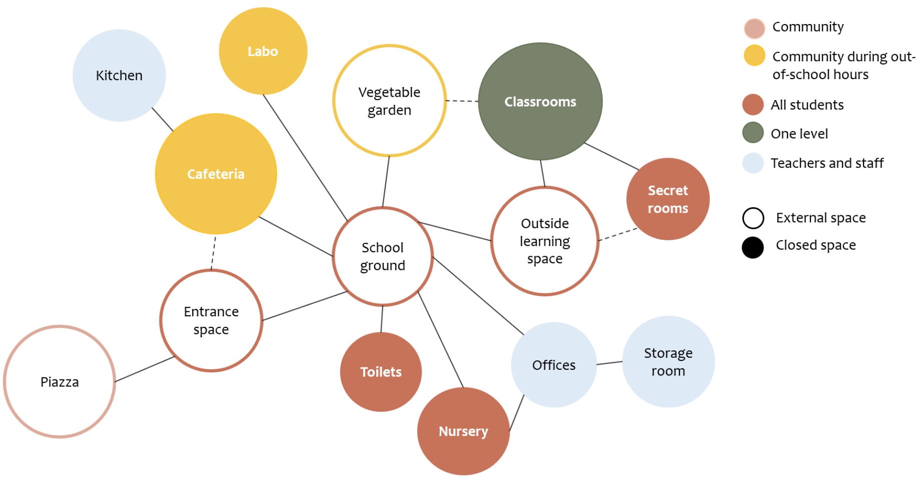


Fig. 5.44 - Functional diagram

2.c. Creation process

Step 1 : Division according to the destination of spaces

First of all, the building was divided based on the destination of spaces : the ones for pupils only were placed further from the road, and the ones accessible to the community outside of school hours were positioned around the main entrance and along the main road. This spatial layout defined two accesses from both roads. Providing spaces for the community is a great way to reinforce its unity as accommodations can be used as much for administrative reasons (councils, meetings...) as for recreative activities to create a meeting place, where one can share knowledge, experiences and values through different activities.

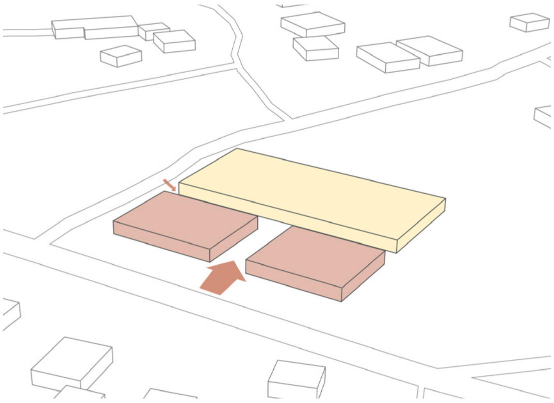


Fig. 5.45 - Division according to the spaces destination

Step 2 : Creation of a courtyard

Then, we created a courtyard in the centre by moving back the walls of the different blocks. The idea is to create a centre echoing to those in the typical villages of the region of Casamance. The large courtyard offers to pupils a nice and large playground shadowed by some large trees.

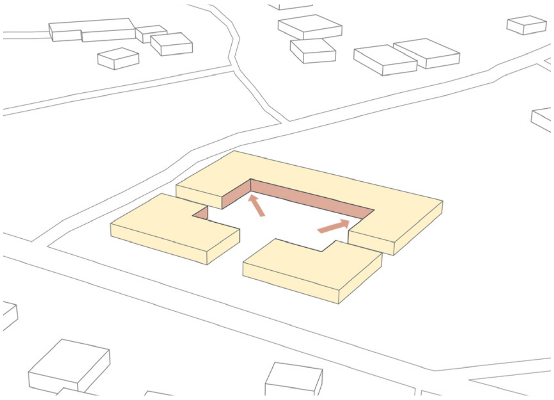


Fig. 5.46 - Division according to the spaces destination

Step 3 : Staggering of modules

We then cut these three large blocks into rectangular modules with dimensions referring to the local buildings of the region. These modules are then placed into a grid depending on their functions. The classrooms are grouped in pairs. The cafeteria is made of two modules as is the laboratory. All these modules are staggered from one another for different reasons. First, their disposition enables the creation of varied spaces and builds a strong relationship between certain modules. It also enables to recall the informality found in the configuration of many villages. Moreover, staggering the modules favours cross ventilation inspired by the vernacular villages of Casamance.

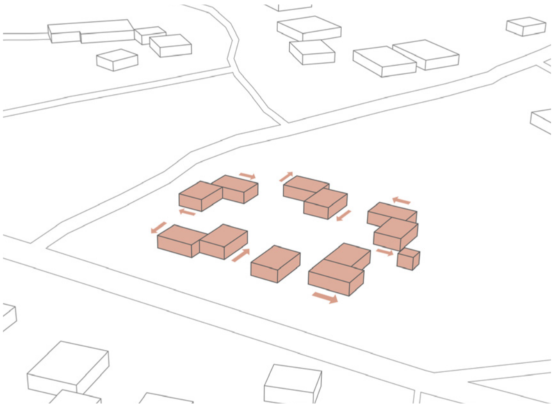


Fig. 5.47 - Staggering of modules

Step 4 : Addition of informal spaces

Informal spaces are added between the modules. They are secret rooms connecting two classrooms modules, an outside auditorium for the laboratory and a terrace for the cafeteria. These spaces make the school more welcoming and can give the children and adults alike a feeling of belonging. As in a home, the school offers room for play and relaxation.

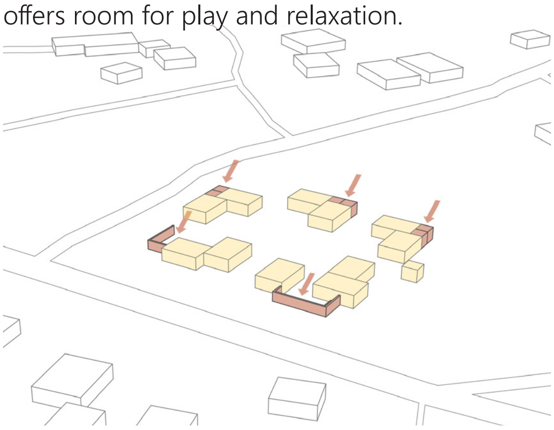


Fig. 5.48 - Addition of informal spaces

Step 5 : Positioning of vegetable gardens

As in many villages, agriculture plays an important role in Baghere. This is why we wanted to add vegetable gardens in the school. They are meant to be maintained by the pupils and by the community. Indeed, the food is harvested for the cafeteria but also for the community in case of surplus. Once again, the relationship between the school and the village is strongly emphasized. The vegetable garden can also be used for teaching purposes.

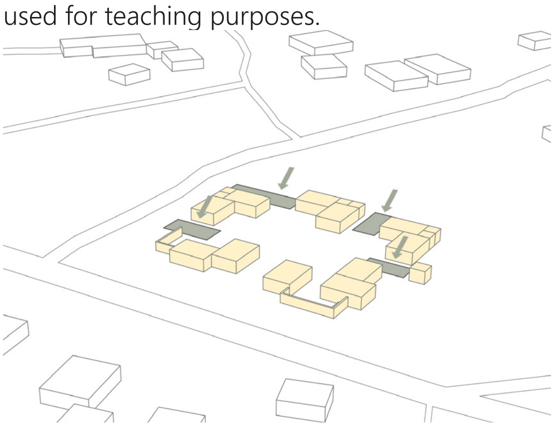


Fig. 5.49 - Positioning of vegetable gardens

Step 6 : Creation of external social places

To emphasize the different relationships in the school, external space has been defined with pergolas and a system of local fabrics to create shaded spaces. The pergolas give the impression of emerging from the roof, extending the roof's structure and connectiong different functions by creating a common shaded areas. This is the case for the classrooms, which share a canopy for outdoor teaching. The one near the laboratory shades an outdoor auditorium and the one next to the cafeteria shades a terrace. Finally, a large one is extending in front of the school to create a nice gathering place for parents.

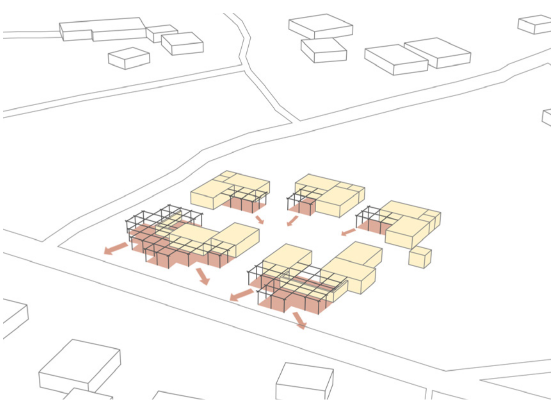


Fig. 5.50 - Creation of external social places

Step 7 : Roof design

We then designed the roof to be adapted to the tropical climate of the region. Its large roof panels protect the raw earth walls from the water, and their reversed position enable the water collection in the centre to be stored and used during the driest season. They also confer a strong symbolic identity to the school, reminiscent of open books and suggesting openness and freedom.

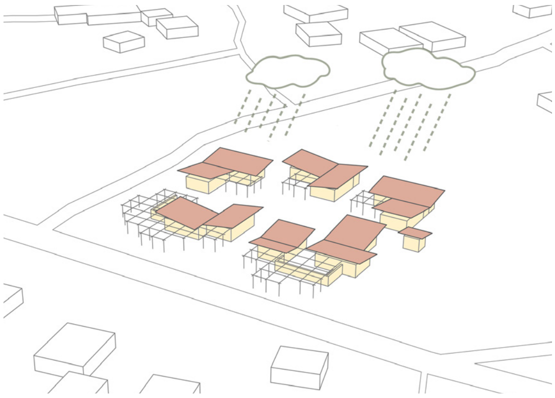


Fig. 5.51 - Roof design

Step 8 : Possibility of extension

Finally, the position of the modules into a grid enables the extension of the school just as traditional settlements expand when the family grows.

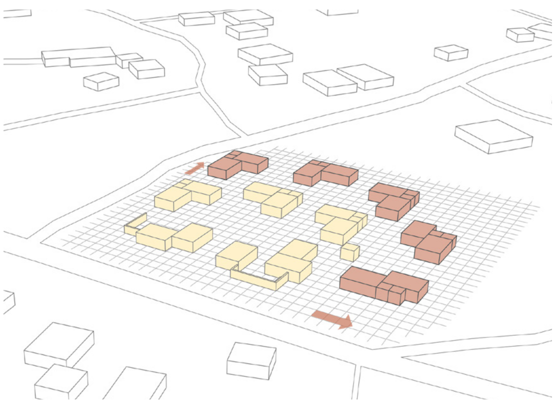


Fig. 5.52 - Possibility of extension

3. ARCHITECTURAL PROJECT

3.a. Masterplan

The school is located at the corner between two streets. Alongside the laboratory and the cafeteria there is the main road leading to the centre of the village and linking the village with the departmental road. The main entrance is located on this road and the second one on the secondary road. This other road is smaller but is still significant as it links the school with the different dwellings of the village.

The boundaries of the school are delimited by vegetation and the walls of the modules. The modules dimensions are modelled on the local buildings to fit in the landscape. The pergolas invite people in by creating a welcoming entrance space. The shaded space can become a social space just as the sacred trees in the centre of the village.

3.b. Plan and functions

The functions of the school are organized as an informal gathering of settlements organized around a centre which becomes the courtyard. Each settlement is itself made of multiple modules that are staggered with each other. They are organized in seemingly random ways that create different relationships between the buildings. This uneven placement, stemming from the local building forms, also defines various types of outside spaces.

The school was thought out to become part of the village and accessible to the community. The entrance is set by the building's arrangement which creates a recess with benches to welcome parents waiting for their kids. A canopy covered in local fabrics emerges from the roofs to shade the entrance. It makes for a cool and colourful space that can also be turned into a market some days of the week. These pergolas coming out from the roofs and providing shading towards the outside are used over in the project to create qualitative and connected outside spaces given the importance of outdoor living in the local customs.

Fig. 5.53 - Masterplan of the school area

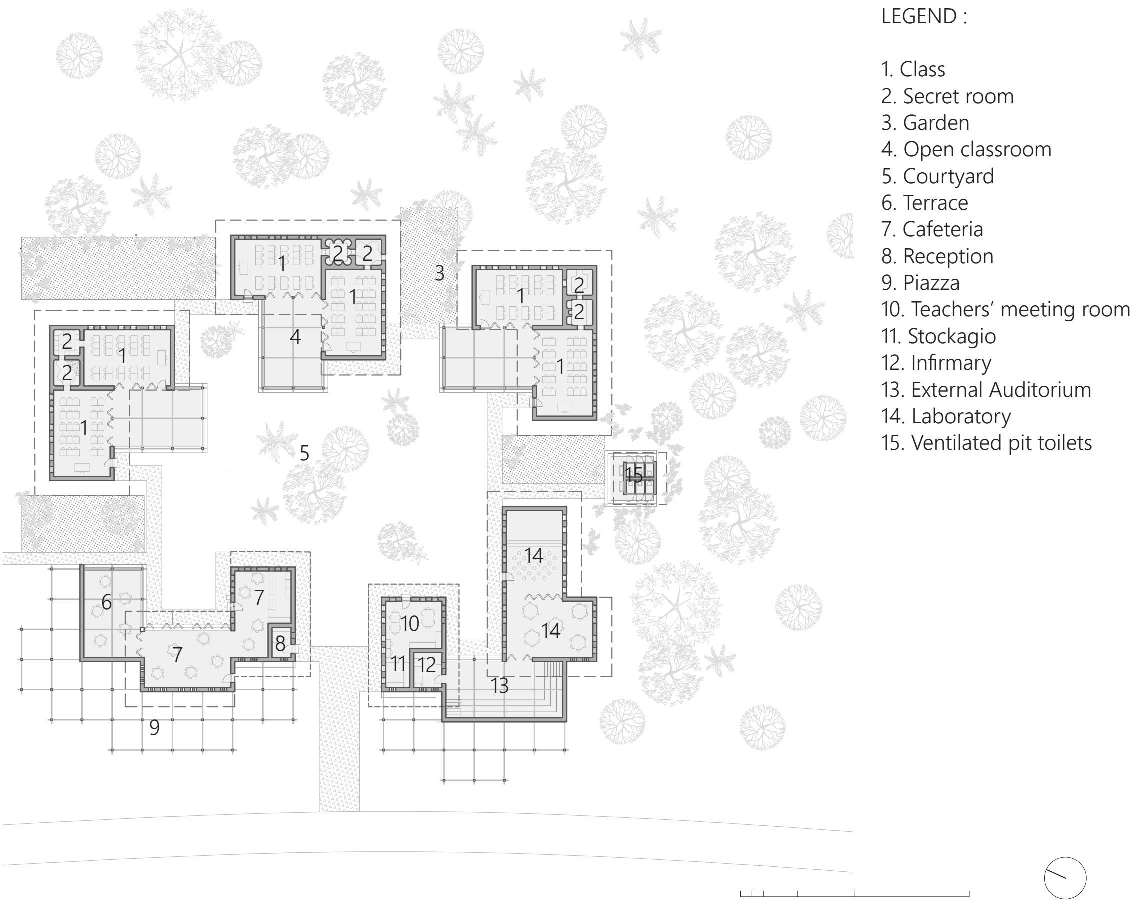


Fig. 5.54 - Plan and functions

The laboratory and the cafeteria are meant to be available to the community during out-of-school hours and thus can open towards the outside of the school. Each of them is made of two connected rooms.

In the cafeteria, one of the buildings is the kitchen and serving, while the other is an eating space. The restauration part can be fully opened with vertical louvred doors towards an outside terrace with fabric shading. The openings towards the main road are small openings in the wall of 9 cm by 17 cm gathered to create windows of 60 cm per 1.60 m to echo the windows of the classrooms. These small openings regulate the light and the direct sunrays inside the building.

Regarding the laboratory, one part can be used as a theatre, and both can be used for workshops. The laboratory is linked to an outdoor auditorium with wood seating steps. This external space is enclosed and set back from the courtyard to create a calm and serene environment for teaching. Once again, the same louvred doors are used to link inside and outdoor spaces and the openings towards the road are the same. The teacher's room and offices as well as the nursery are next to the entrance and open towards the outdoor auditorium.

The classrooms are organized in pairs of two modules. Their roof structures extend and merge into a pergola that creates a shaded area for outside teaching activities. The peripheric wood shutters of the classrooms can fully open to unify the inside and outside areas. The openings towards the exterior are wood louvres of 60 cm per 1.60 m. Their position can be changed depending on the time of the day to regulate the light and the direct sunrays inside the building.

Besides, each class has a secret room, accessible from the back of the classroom and connected to the other classroom's. This room is a children-only space adapted to each age and offers a cosy space to rest, read and escape from the traditional teaching environment. The earth material is being explored in all its versatility in these secret rooms creating organic and comforting shapes. The openings were designed to have the same luminosity found in

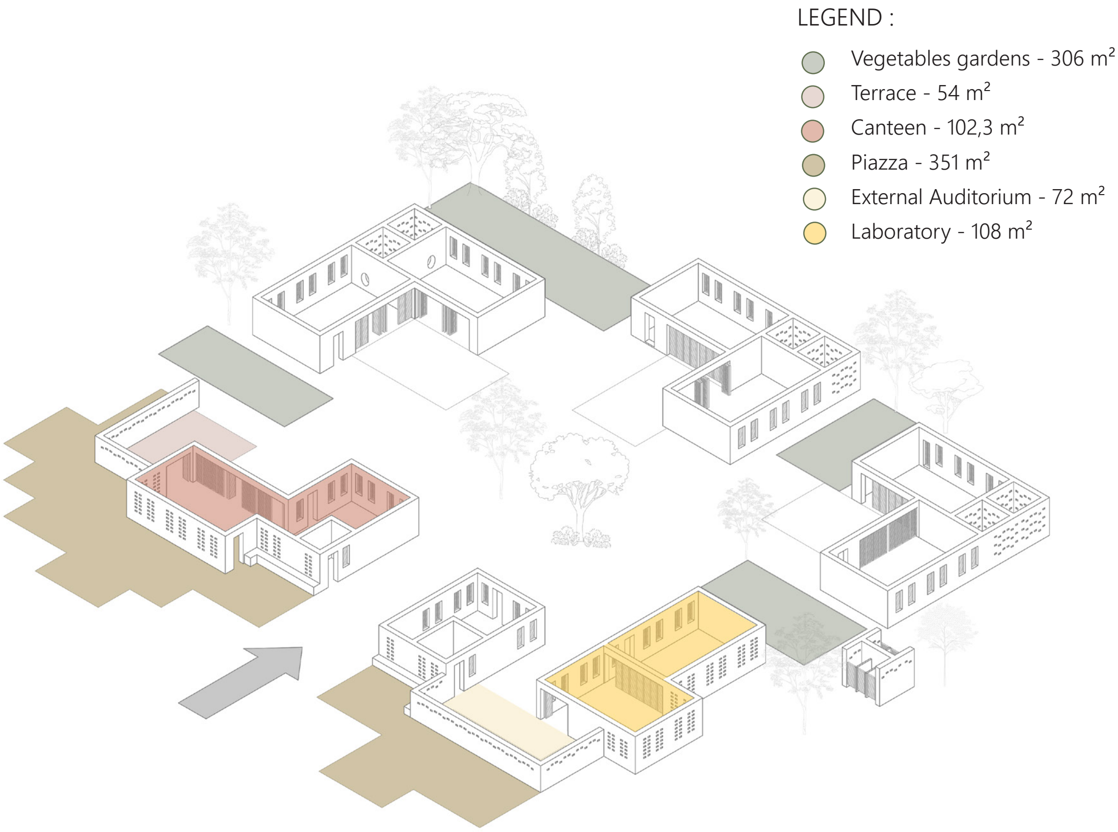


Fig. 5.55 - Functions diagram - Community accessible spaces

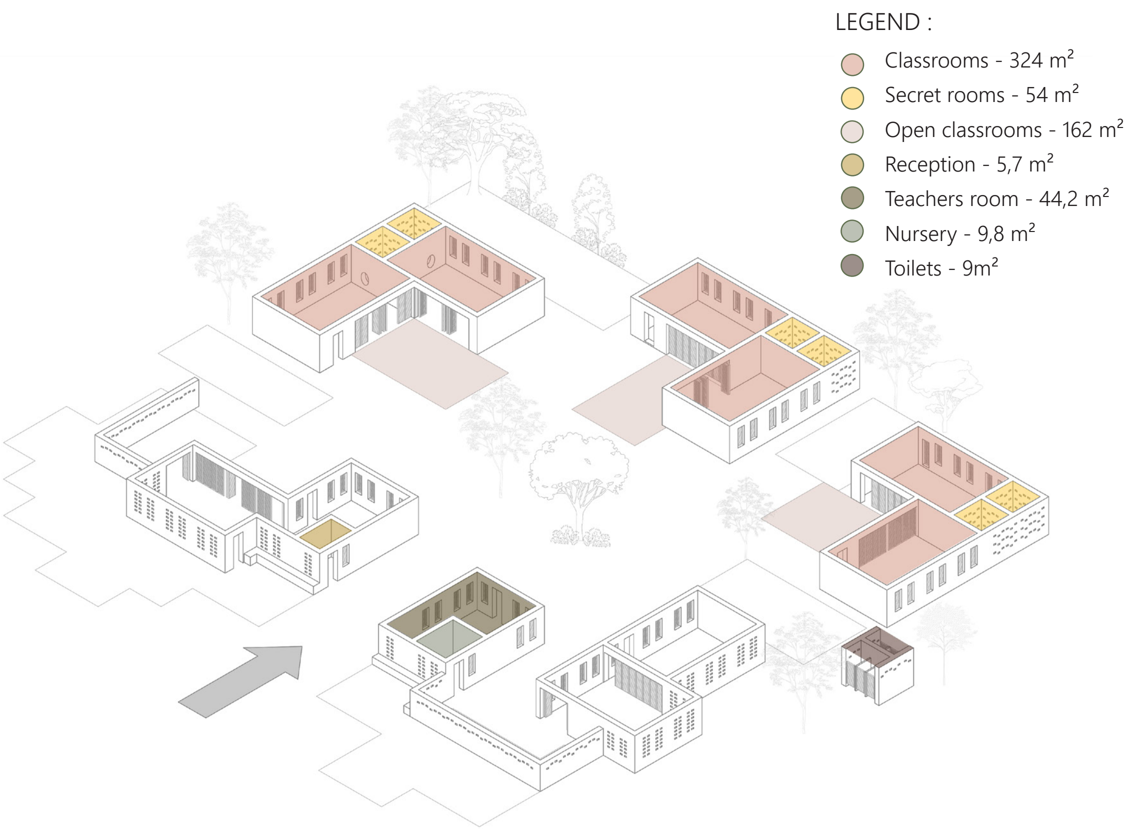


Fig. 5.56 - Functions diagram - School spaces

local houses. As houses aren't much used during the day they are often dark with small openings. Having the same luminosity as the house enables to create a comforting space. Thus, to bring light into the secret rooms, the walls are perforated in a playful pattern.

Along the secondary entrances, vegetable gardens are placed to serve as means of education and of provision for the cafeteria. They are maintained by the pupils, the school staffs but also the community. Indeed, the idea is also to create further connections with the local agricultural community.

The rainwater is collected by the inverted pitched roofs to be used in the cultivation of vegetables and for basic hygiene. This last topic is crucial to consider in the design of schools in sub–Saharan Africa. Hence, the nursery has been placed in a calm place, directly connected to the teacher's offices. For sanitary purposes, the toilets are located further from the social spaces, and are thought to be ventilated pit latrines. However they are easily accessible from the courtyard.

In short, the project is designed as a village, enabling a huge variety of uses and connections. It provides spaces open to different publics depending of the school schedule, from children only to the whole local community. Its layout and configuration in a grid also enables future extensions, to make it an ever-evolving educational space.

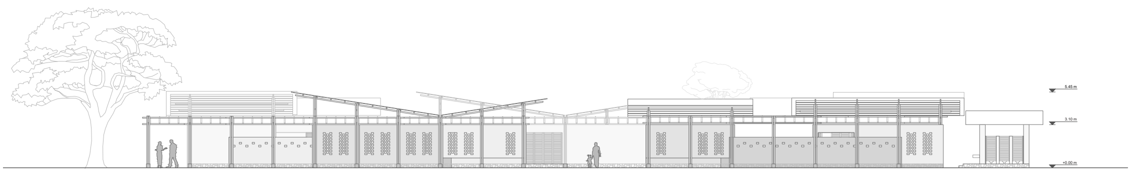
3.c. Elevations and sections

From the main entrance elevation, the concept of a village is directly noticeable. Indeed, the informal arrangement of the modules create the image of a village. Moreover, the movement created by the roof gives an idea a liberty, as if each group of module was a house that chose the direction of their roof. Once again underlining the informal arrangement of the spaces and the idea of village are underlined. The staggering of the different parts of the school emphasize their different spaces and their function.

In the sections, the sequence of the different spaces takes shape. Indeed, in the section AA', we can easily see the spaces accessible to the community. The cafeteria has a direct access to the terrace. In section BB', we also clearly see the continuity between the indoor space of the laboratory and its outdoor space with the external auditorium. The connection between classroom and secret room is also well illustrated.

Moreover, to enable representation or shows, a little platform of 60 cm is created for a stage. Regarding the ceilings of all indoor spaces but secrets rooms, the vaulted ceiling, parallel to the shortest wall recall vernacular ceilings of the region.

Finally, it is noticeable how the roof structure extends and merges into a pergola to create shaded areas for outside activities and a perfect public space in front of the school.



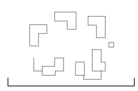
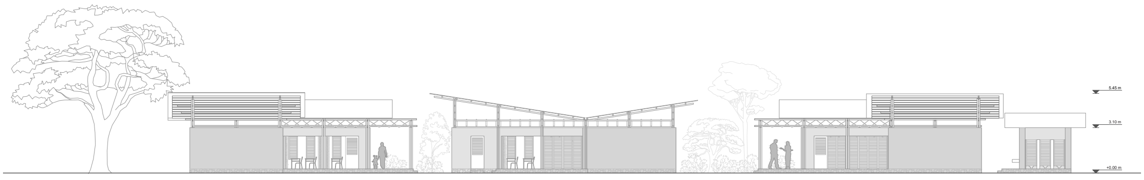


Fig. 5.57 - Entrance elevation



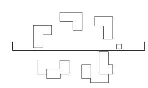
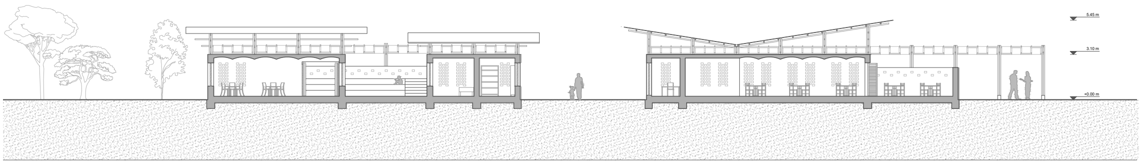


Fig. 5.58 - Courtyard elevation



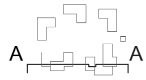
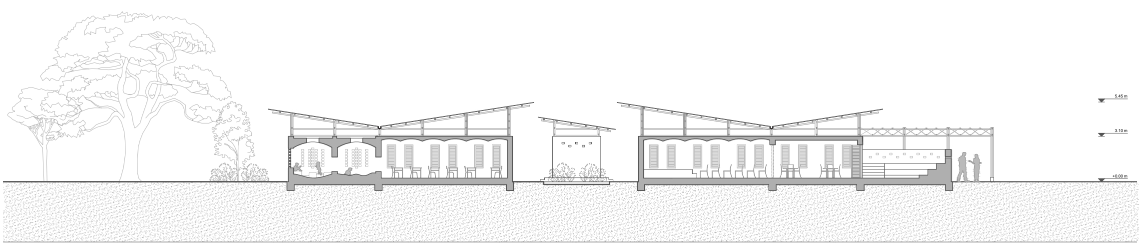


Fig. 5.59 - Section AA '



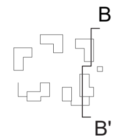


Fig. 5.60 - Section BB'

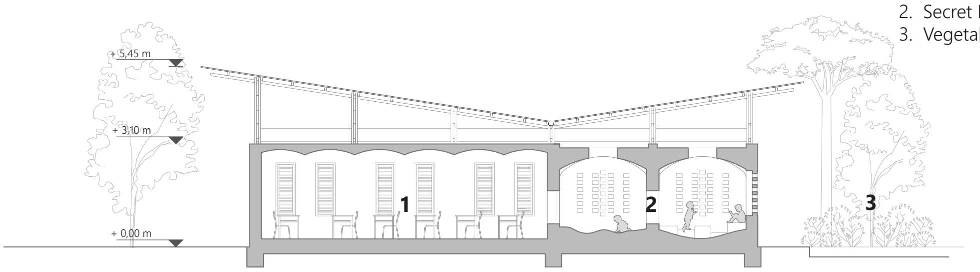


Fig. 5.61 - Class section

3.d. Materials

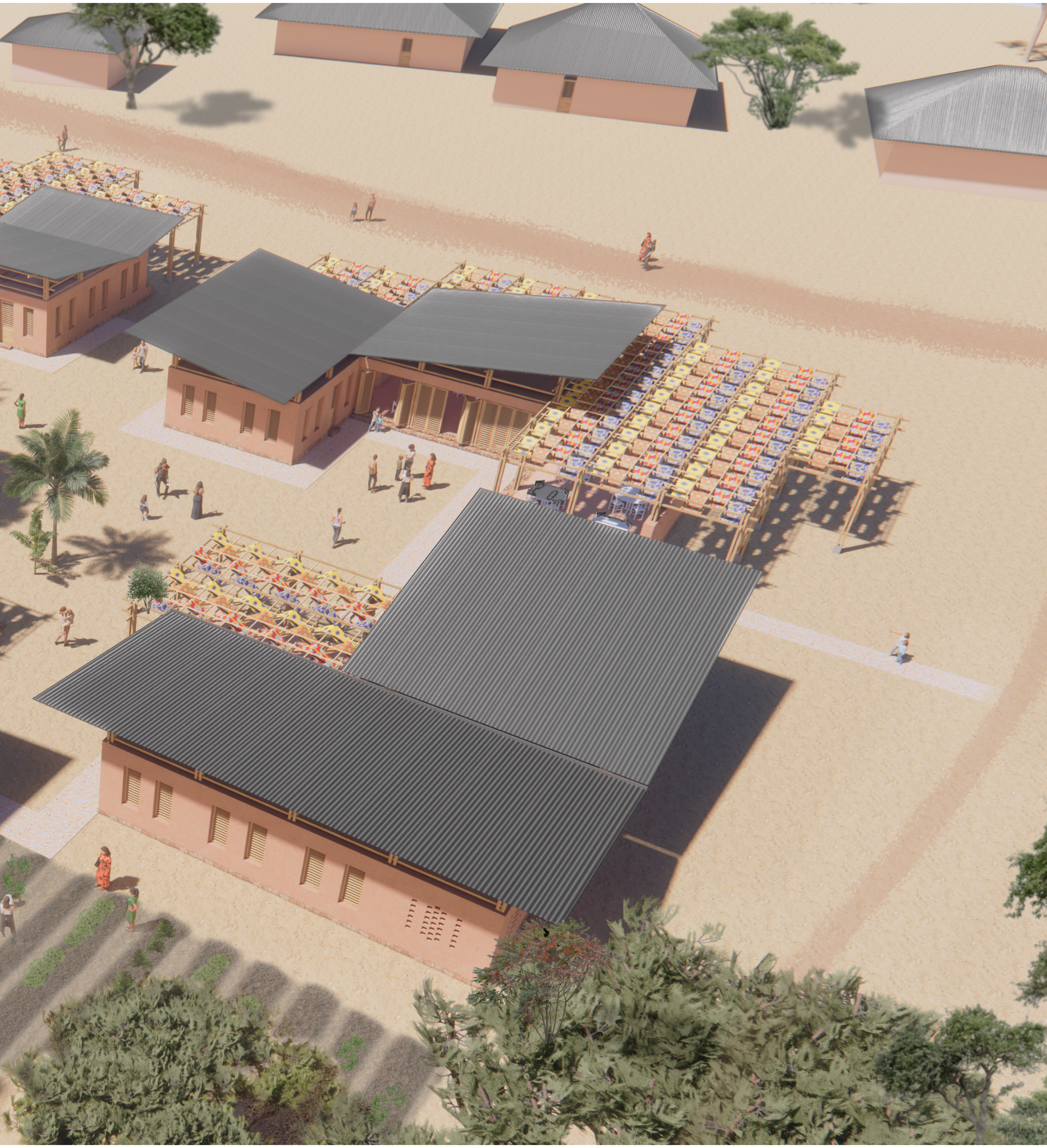
The compressed raw earth bricks were chosen as the main material for construction since it is a local material and easy to build with. It is also an insulating material, which responds well to humid climates. The bricks allow the creation of vaulted ceilings which have good properties for acoustics and ventilation, of utmost importance in the area.

For good support, vaulted ceilings require IPE type beams, which weight is supported by earthen walls. The roof is supported by a wooden structure. The local samba beams come in a 6 x 8 cm size. Hence, the pillars were made connecting four beams together. This also gives the illusion of more elongated pillars while allowing to easily connect the beams in the middle of the pillars for the pergolas' structure. Wood was preferred, whenever possible, to metal structural elements for its sustainable character and its local availability.

Corrugated sheets are used for the roof because of their low weight and low need for maintenance. They are inverted pitched roofs, each sloped on one module, while the water gets collected by a zinc gutter in the middle. The metal roof can get hot and noisy under the Senegalese climate, so the double roof technique was employed with an insulating earth roof, and a space for natural ventilation under the metallic cover.

Regarding the pergola, they are made with rosewood beam and the fabric wrapped to it is easily removable and changeable.

Fig. 5.62 - Aerial r



ender of the school

Fig. 5.63

Fig. 5.64 - Veg

- *Piazza*

etable garden

Fig. 5.65 - Exte

rnal classroom

Fig. 5.66 - Auditorium

Fig. 5.67 - Secret room

VI. CONSTRUCTION DETAILS

VI. CONSTRUCTION DETAILS

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1. FOUNDATIONS

1.a. Building elements

The foundation is made of locally sourced lateite stones, joined with a cement-based mortar. It is composed of a 60 cm-deep, 50 cm-large footing and of a 50 cm-high emerging stone wall on which are placed the compressed earth bricks. This base course is necessary to protect the earth masonry from splashing rain and humidity raising from the ground. [1] The height of 50 cm was considered adequate in a context of heavy rain for a building with sufficient roof overhangs. [2]

The foundation is accompanied with a peripheral drainage system composed of a PVC channel at the bottom of the trench and a gradient of stones and gravel that constitutes a draining and filtering system as explained in Fig. 6.1. The heavy rain season of Baghere makes the correct evacuation of rainwater an important characteristic of the project. The bottom of the foundation wall is covered with a baseboard, also made from laterite stone, which is raised up to 20 cm above the ground and prevents water from entering the structure.

The raised floors are positioned on repurposed tyres found locally and filled with earth and gravel. These punctual supports are positioned on a bed of compacted gravel for stability and drainage purposes.

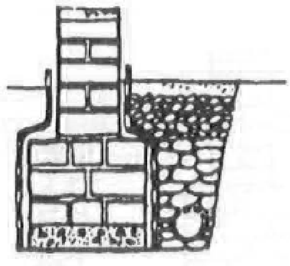

Fig. 6.1 - Foundation design @UN-HABITAT

1.b. Construction process

A 60 cm-deep trench must be dug along the future walls while the internal part of the future building must be 35 cm deep. The earth is reserved on the side to serve as a construction material. The stone foundations are then built with laterite stones and cement-based mortar.

Above this foundation, a wall of stone, high 50 cm, must be put up to avoid direct contact between the earthen walls and the soil that can carry humidity. Along the foundation, on the outside, the drainage pipe is placed, and the trench is filled with stone and gravel. A thin layer of earth covers it. The baseboard is made of flatter stones and is placed all along the outside. The joints have to be raked out to prevent water infiltration. To prepare for the floors, a 15 cm-deep layer of gravel is poured, levelled, and compacted. Reused tyres are then placed, levelled, and filled with earth and stone to serve as structural supports for the raised floor.

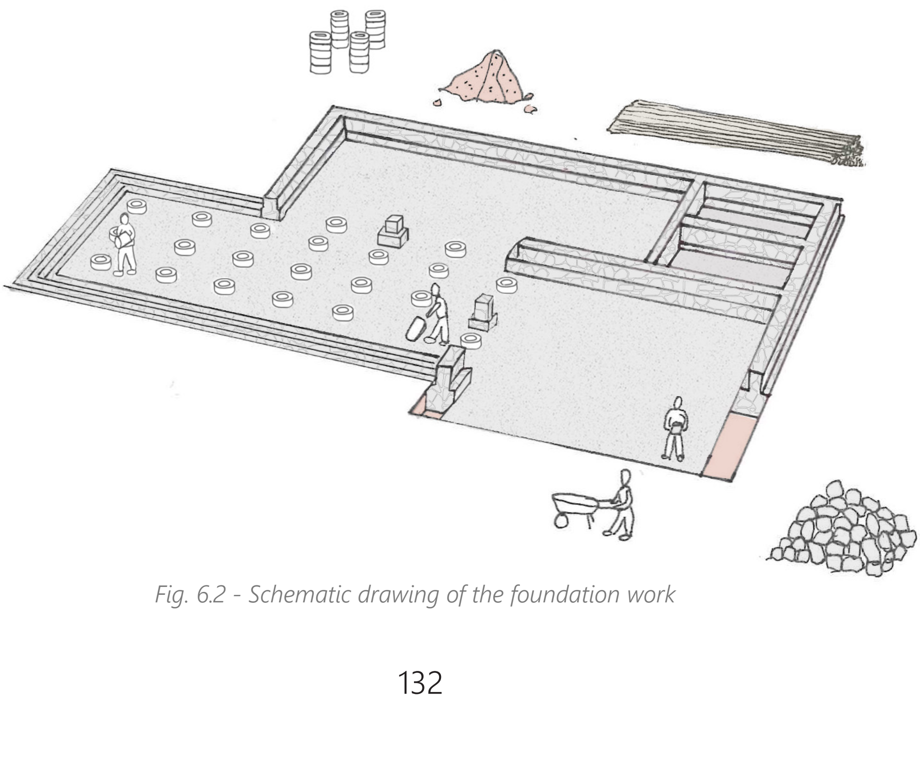

Fig. 6.2 - Schematic drawing of the foundation work

2. FLOORS

2.a. Building elements

- **Indoor floor**

The indoor floor, named as F01, is a raised floor, to reduce its exposure to water in this humid climate. It is built on a wooden structure resting on tyres, 20 cm above the ground. The support is made with samba wood planks covered with a straw mat to contain the filling material and reduce dust. A 10 cm-high layer of clay-straw lightweight loam is poured to serve as a filling and insulating material, with a low density of around 700 kg/m^3. Hard wearing surfaces need to have a good resistance to abrasion, a java smooth aspect with no cracks and be waterproof. Therefore, the loam composition for the lining of the floor must be specifically studied and tested. The exposed surface is coated with 4 cm of clay mortar stabilized with lime and casein. This mortar is made with a high content of sand to avoid cracking and 6% by dry weight of stabilizing agent made from one portion of hydraulic lime and fivre portions of white cheese with additional chalk. This stabilization gives the surface sufficient hardness while creating a waterproof barrier. [3]

- **Outdoor floor**

The F01 floor is also used outdoor for the outside social areas. The raised floor is in this case encircled by stone stairs which serve the same structural purpose as the stone foundation. The layers are all the same except for the finishing layer which is stabilized with cement to be more durable under outdoor conditions.

The pathways are made of stabilized earth. The first layer is 15 cm-thick compacted gravel that serve as a foundation. On top of it, a 5-cm thick layer of cement-stabilized earth is laid and ornated with repurposed broken tiles found locally, giving a playful render.

Component details :

Floor F01 :

1. Loam mortar made from earth, lime-casein stabilizer and additional sand, Thickness : 4 cm
2. Clay-straw lightweight loam, Thickness : 10 cm
3. Straw matting, Thickness : 0.5 cm
4. Samba wood boards, Thickness : 3 cm
5. Samba wood beams, 8x12 cm
6. Pneumatics filled with earth and stone, Height : 20,5 cm
7. Compacted gravel, Height : 15 cm

Floor F02 :

1. Repurposed broken tiles, Thickness : 1 cm
2. Stabilized earth with cement, Thickness : 5 cm
3. Gravel, Thickness : 15 cm

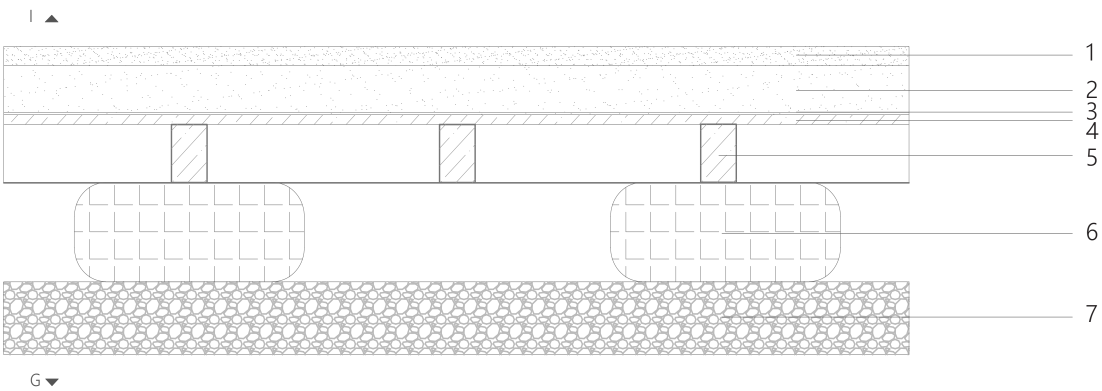

Fig. 6.3 - Components detail of the raised floor F01

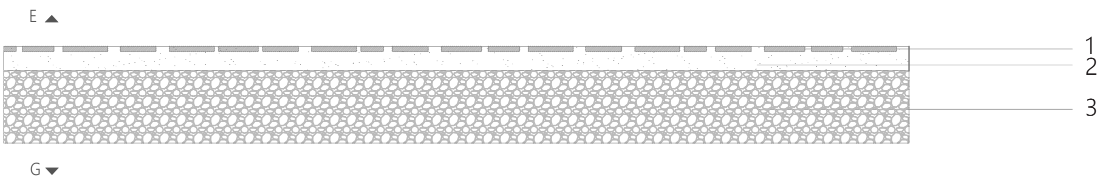

Fig. 6.4 - Components detail of the outdoor pathways F02

2.b. Construction process

- **Structure and support**

The first step to the construction of the floors is the positioning of the samba wood structure, resting on the footing of the stone foundations and on the tyres. They are linked together with simple L-plates and screws. The wood boards are then screwed on top, and the straw mat is spread over them.

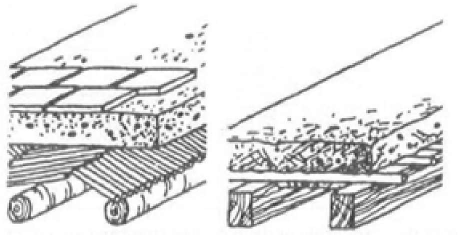

Fig. 6.5 - Raised floors designs @UN-HABITAT

- **Insulating filling**

The clay-straw mixture is prepared by hand in a tank with a shovel. The straw has to be cut into pieces shorter than the thickness applied, in this case 10 cm.

The proportions of straw and earth have to be tested for consistency but should be around 65% of soil for 35% of straw. The layer of lightweight straw loam is poured with a wheelbarrow and levelled. This layer must be dried before applying the hard coating. An insufficient ventilation during the drying process could lead to the development of fungi inside the loam, it should therefore be carefully controlled. [3]

Fig. 6.6 - Clay-straw lightweight loam

Fig. 6.7 - Broken tiles @Balouo Salo

- **Protective coating**

For the coating, the stabilizing agents: hydraulic lime and fat-free white cheese are mixed vigorously without water for two minutes and then allowed to stand. Loam with a high clay content is then mixed with sand, 10% chalk and 6% by dry mass of this stabilizing mixture. [3] This finishing mortar is applied in two layers for a total thickness of 4 cm. They are comparable to plasters with low moisture content and the surface can be smoothed with a trowel. [1] Lime can be irritating for the skin, and workers should wear appropriate gloves. After fully drying, the floor surface is coloured and waxed to limit damages and provide further waterproofing. The waxing process must be regularly implemented. On the base of the walls a stone skirting base is to be applied with loam mortar.

For cement-stabilized earth, the mix must be done little by little to be applied directly before hardening. The cement is mixed with earth before water is added. The stabilized earth must be mixed continuously during the application either with a concrete mixer or simply with a shovel. After a few layers of stabilized earth, the broken tiles are positioned and more stabilized earth is poured over them and used as grout

3. WALLS

3.a. Building elements

- **Bricks**

The walls are built with compressed earth bricks in the standard format: 29.5 x 14 x 9 cm. This format allows the construction of loadbearing walls with two or three courses and is not too thick in order to facilitate the drying process. [1] The bricks are made of earth, water, gravel, and vegetable fibres. The exact composition was the object of a study developed in part VII of the thesis. The wall is made of two courses of bricks for a wall-thickness of 29,5 cm. The thickness is therefore superior to 1/10 of the height of the earth part of the wall (2,6 m), rule of thumb for the construction in earth bricks. [2]

- **Mortar**

The mortar used for the construction is made of clay, water, and additional sand. The sand's purpose is to avoid any excessive cracking when the mortar dries. The clay content must be found between 4 and 10%. [3]

- **Plaster**

On the outside, a clay-lime plaster is used in a thin layer. It is made to protect the walls from erosion while letting through the humidity absorbed in the blocks, thus conserving the hygrothermal properties of raw earth. It also gives a smooth finish and can be coloured, to avoid the whitewashed effect of lime. On the inside, a simple clay plaster is used to make a smooth surface, while having the same properties as the wall.

Component details :

Wall W01

1. Clay plaster, Thickness : 4 cm
2. Compressed earth bricks in flemish bond pattern 23.5 x 11 x 9 cm
3. Loam mortar, Thickness 1,5 cm
4. Lime-clay plaster, Thickness 2 cm

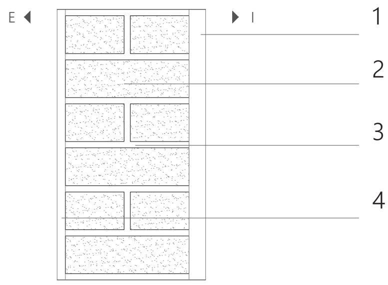

Fig. 6.8 - Components detail of the wall W01

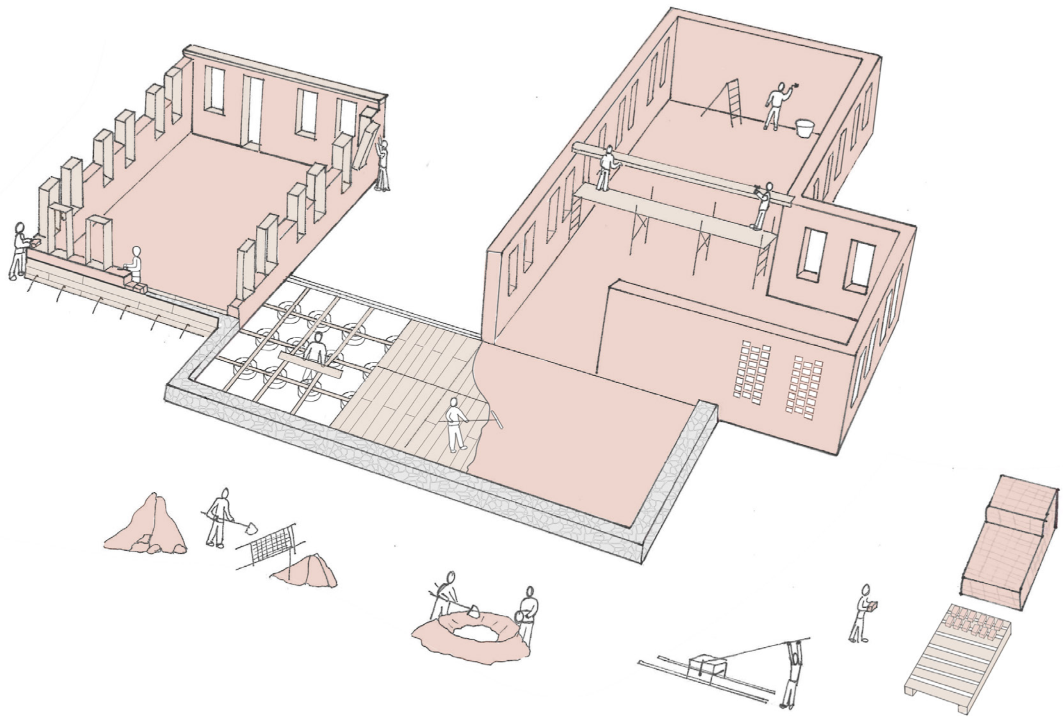

Fig. 6.9 - Schematic drawing of the flooring and masonry work

3.b. Construction process

- **Making the bricks**

The earth excavated is stored by depth, and the earth coming from the bottom of the foundation trenches serves for the creation of the bricks. The first step to the making of the bricks is the screening of the earth through a 10 mm screen to make sure no large aggregate is found in the mix. Then, the water and vegetable fibres are added and mixed into the earth.

The mix is poured into the CINVA-RAM manual press, activated by means of a 3-meters-long pole. The brick is formed by one pression on the pole, the person applying all his weight. Another person should stand on the opposite side of the press to act as a counnterweight. The bricks are then deposited in rows, on a pallet to dry in the sun. For a faster process, the bricks are positioned on their side. The bricks are considered completely dried after 28 days. [4]

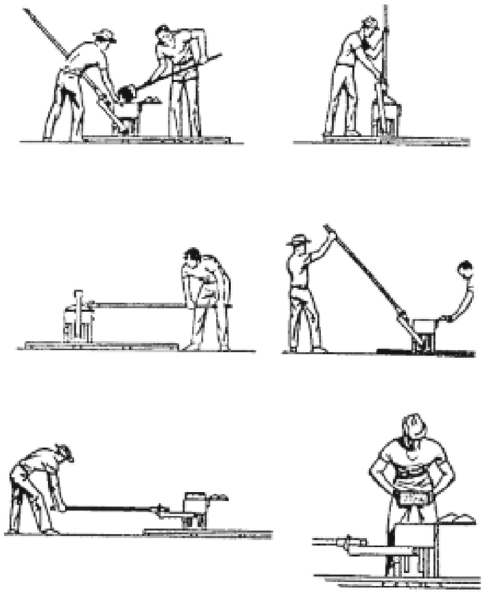

Fig. 6.10 - Operation of a CINVA RAM @G Minke

Fig. 6.11 - Earth blocks drying @Nairaland

- **Making the mortar**

The earth used to make the mortar must be sieved through a 5 mm screen. The mortar should be made with an important percentage of coarse sand to arrive at a low clay content between 4-10 %. It should be well mixed, without any lumps. The content of water should be just enough to be able to spread it (usually around 30% in volume). When the brick is laid on top of the mortar bed, no leakage of mud or water should be observed. The mortar should be mixed 24 hours before its use, to make sure it is adequately hydrated. [1] Large quantities of mortar can also be made in advance and water could be added just before the use to make it workable.

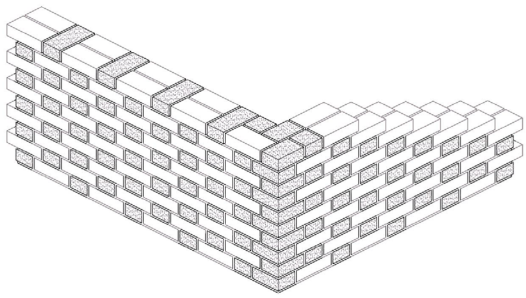

Fig. 6.12- Flemish bond diagram

- **Laying out the bricks**

The laying out of the bricks results in the technical and aesthetic quality of the building. One technique for masonry is to use site boards fixed around the stone base course and stretch alignment strings between saw cuts. The site boards should arrive at the same level as the first brick course, so it will be precisely laid and serve as a reference for the next courses. For the vertical distance, gauge rods should indicate the levels of openings, beams and of the height of the wall. [5] The bricks are simply laid down, with a layer of mortar of 1,5 cm on the horizontal and vertical joints. If the layer of mortar is too thin, the structure could crack, if it is too thick, the overall resistance of the wall would diminish. For better adherence, the bricks and the mortar bed should be wet. Protection against the sun and wind during the laying out process is advisable. Just after laying, the joints should be raked out to 2-3 cm, before filling the joint flush with mortar and finning with a jointing tool. If necessary, the blocks can be cut easily using a simple saw or even a trowel and a hammer. [2]

The bonding pattern used in our building construction is the Flemish bond (cf. Fig 6.7). It allows us to make staggered openings and has the best shear resistance out of the traditional two courses bond patterns. [6] There should be no overlapping of vertical joints as they would result in important vulnerabilities. Half bricks can be used in the corer design.

- **Plastering**

The areas to be plastered should be dry and rough. The wall can be sprayed with water and then grooved diagonally 2-3 mm deep. While the surface is still moist, it can be primed with thin lime water. A mix of one portion of hydraulic lime and 15 portions of water has been found to work accordingly. The plaster is then applied in 2 layers of around 10 mm. The second layer should be laid while the first one is still moist. Lime plaster cures when it is hydrated, therefore the surface should be moistened regularly with a damp fabric. [7] If cracks are observed, they can be closed by applying lime water and rubbing the surface with a trowel. The internal clay plaster can be applied in one unique layer. The larger surfaces may require reinforcement, in which case chicken wire can be used, especially for the thicker layers inside of the secret rooms for example.

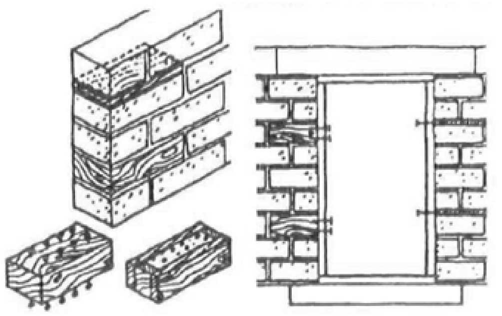

Fig. 6.13 - Gringo blocks @UN-HABITAT

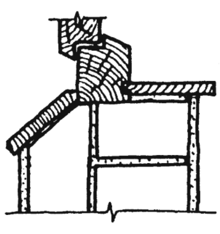

Fig. 6.14 - Window sill @UN-HABITAT

4. OPENINGS

4.a. Building elements

The openings must be treated with care in earth blocks masonry, because of the concentration of stresses around the frame, and the joint between different materials. The openings are therefore dressed in wood, with lintels, sills and jambs protruding to protect the edges of the earth masonry. [8] The lintels have been specifically dimensioned structurally and extend 30 cm on each side of the opening according to the New Mexico Building Code. [1] The openings have also been purposefully designed as rather thin to not compromise the structural integrity, with a width lower than 1/3 of the height of the wall. Where larger openings are found, a wooden structure has been chosen over the loadbearing masonry. The openings are also located at a minimum distance of 45cm from the angles of the buildings according to the New Mexico Building Code. [1]

The openings are of three types : the basic wooden doors, serving as the main entrance to each space, the windows, made with louvers rotating around their centre and the accordion hanging doors, made to separate or merge spaces in a flexible way.

4.a. Construction process

The wood should be treated against humidity damages, either by roughing, studding, or flashing. It should also be given a treatment against fungi and termites. The wooden frames for all openings are built on site. They are consolidated at the angles with temporary wood triangles. They are placed on a mortar bed in the adequate position for the masonry to be built around it. The two rows of bricks under the window sill should be built with stabilized bricks using lime-casein to avoid water damage. During the plastering process, a particular attention should be given to this area. Along the windows and doors jambs, some wood blocks also called gringo blocks are placed in the masonry for the jamb to be nailed down to. They are planted with nails protruding all around to adhere better into the masonry. This system is designed to help answer to the stresses created by the opening and closing of the doors and windows. [2]

5. CEILINGS

5.a. Building elements

- **Jack arches ceiling**

The ceilings to most spaces are made with jack arches. The structural elements are iron IPE beams. Arches made of compressed earth blocks are supported on the lower flanges of the beam. The arches span over 1,5 m with a height change in the centre of 1/10 of the span. On top of the arches, a clay-loam lightweight fillings also helps joining the arch while being insulating. On top of it, a 2 cm layer of lime-casein stabilized plaster provides resistance and some waterproofing ceiling, which is further water protected by the roof.

- **Coffered ceiling**

The ceiling of the secret room is made with a wooden coffered structure. This structure is composed of 8 x 12 cm samba wood beams. Wood planks are connected to the lower side of the beams and protected with a straw mat. Lightweight loam is poured between the framed structure although a skylight is created in the middle. The coating is once again made of lime-casein stabilized loam mortar. The particularity is the vault created internally. Some wooden dowels are fixed between the wood boards of the ceiling and some wood supports in the wall. The filling of the vault is made of lightweight straw loam and the coating of clay-lime plaster.

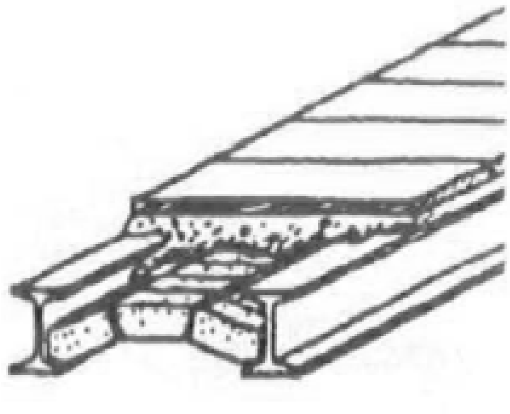

Fig. 6.15 - Jack arches ceiling @UN-HABITAT

Component details :

Jack arches ceiling C01 :

1. Loam mortar made from earth, lime-casein stabilizer and additional sand, Thickness : 2 cm
2. Clay-straw lightweight loam, Thickness : 10 cm
3. Compressed earth bricks, 29.5 x 14 x 9 cm
4. Iron IPE 180 beam, Height : 18 cm

Coffered ceiling C02 :

1. Loam mortar made from earth, lime-casein stabilizer and additional sand, Thickness : 2 cm
2. Clay-straw lightweight loam, Thickness : 10 cm
3. Samba wood beams, 8 x 12 cm
4. Straw matting, Thickness : 0.5 cm
5. Samba wood boards, Thickness : 2 cm
6. Clay plaster, Thickness : 4 cm

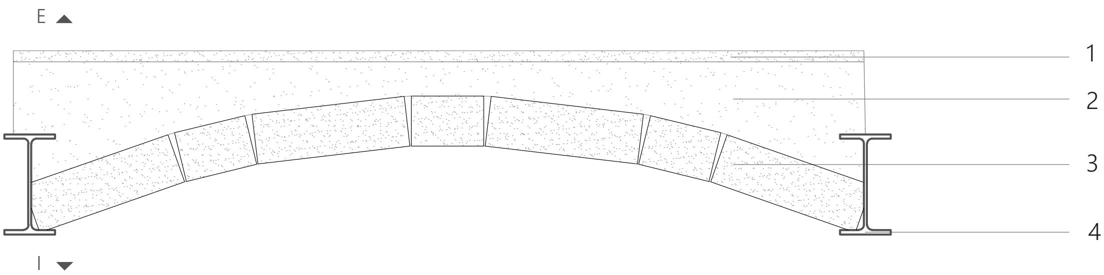

Fig. 6.16 - Component details of the jack arches ceiling

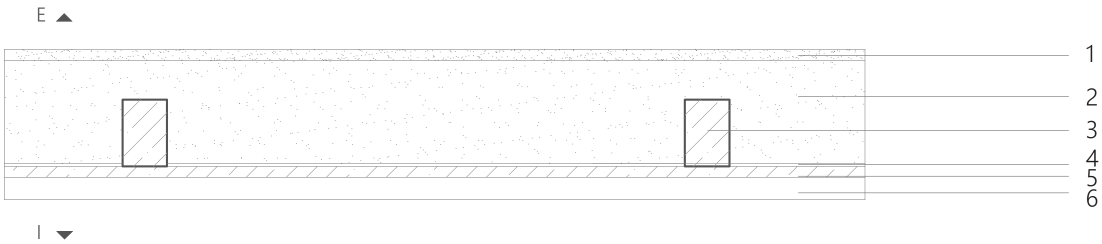

Fig. 6.17- Component details of the coffered ceiling

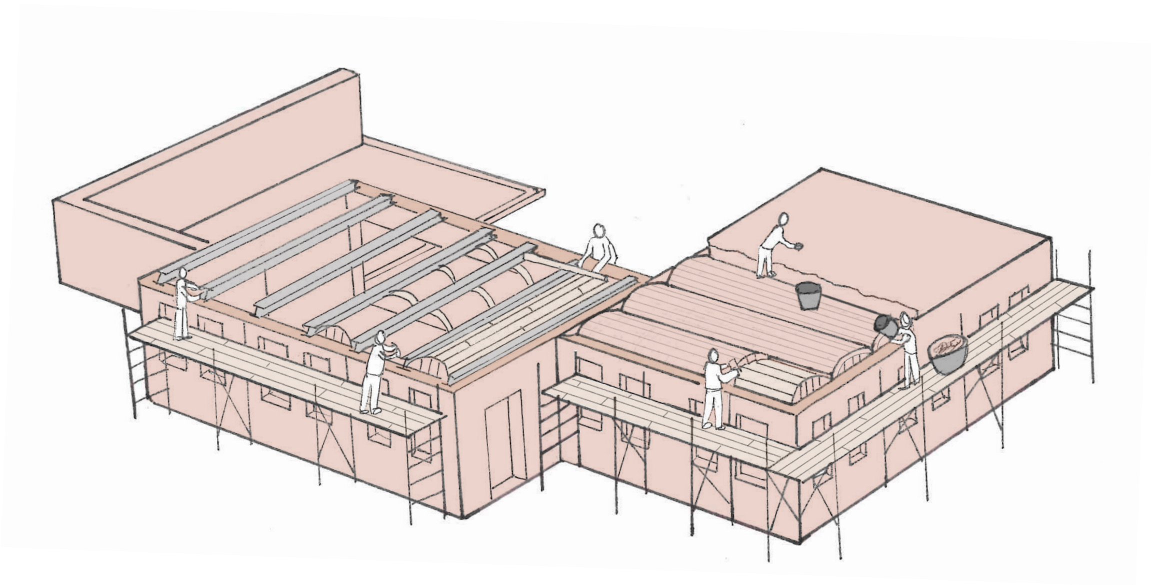

Fig. 6.18 - Schematic drawing of the ceiling building process

5.b. Construction process

- **Jack arches ceiling**

The IPE beams are first positioned and connected onto the wood ring beam. Another ring beam is placed on top, and the masonry wall can be completed. Then, the formworks are built in wood between the iron beams for the bricks to be laid on top in a Flemish pattern. The vertical joints between bricks are filled with mortar. After the masonry is dried, the lightweight loam is poured over it and let dried. The formwork can only then be taken out and reused for the next arches. [2] Finally, the ceiling is coated with lime-casein stabilized loam mortar in two thin layers.

- **Coffered ceiling**

The wood structure to the secret rooms is built the same way, screwed between two wood boards inside the masonry wall. Then, wood planks are placed under the coffered structure and screwed in place. Straw mats are laid on top of the planks and the clay-straw filling is poured. Once it dries, a stabilized coating is applied the same way as for the F01 ceiling. On the inside, some wooden branches are connected angled between the wood support planks and wood anchors in the wall. A network is created using branches positioned horizontally.

Clay-straw lightweight loam is pressed following the wattle-and-daub technique. To check the appropriate consistency of the loam, a 10 cm ball of loam can be thrown 1 m high and the resulting shape should have a 13-14 cm diameter. [3] To make the smooth vaulted shape on the inside, the earth plaster can be applied in heavier layers, for a maximum thickness up to 8 cm. For reinforcement, chicken wire can be used as support for the plaster.

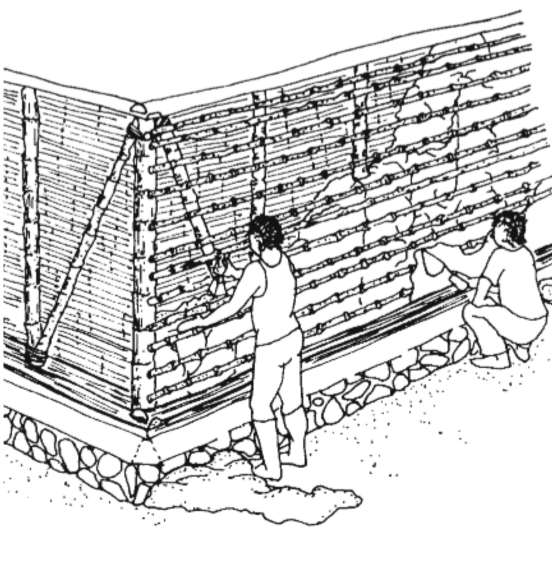

Fig. 6.19 - Wattle-and-daub @G Minke

6. ROOF

6.a. Building elements

The wooden ring beam on top of the IPE beam serves as an anchoring point for the wooden structure of the roof. Its purposes are to distribute the loads and rigidify the earth structure to avoid damages due to shrinkage, swell, shear and normal stresses. [2] For this purpose, the ring beam is solidly anchored to the metal beam by means of bolts. It is also anchored 50 cm-deep into the wall with iron wires attached to metal rods placed in the masonry.

The wooden pillars are made of four 6x6 cm beams joined together. This size of beams is easily available and cheap. These pillars also have an aesthetic aspect and allow easy connection of the rafters.

The roof is made of iron corrugated roof sheets supported by 6 x 12 samba wood rafters. This material allows for a gsecure impermeability and doesnt require much lmaintenance in comparison with thhatch roof. It also has the advantage of being lightweight therefore it can be supported byearth brick masonry.

Component details :

Roof R01

1. Corrugated iron roof sheet, Thickness : 0.75 mm
2. Samba wood support beam, 12 x 6 cm
3. Samba wood beam, 12 x 6 cm

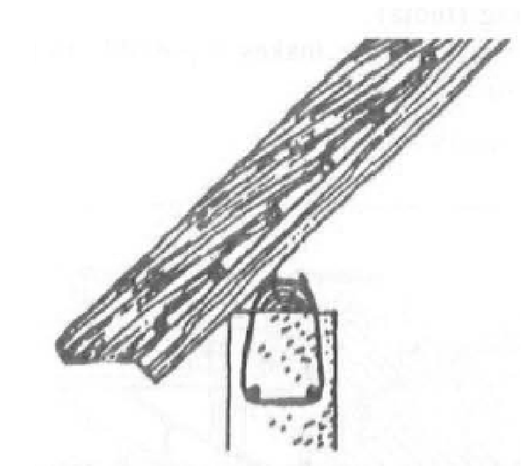

Fig. 6.20 - Ring beam anchoring @UN-HABITAT

6.b. Construction process

- **Ring beam**

To allow the anchoring of the ring beam in the wall, the last five courses of bricks should include some perforated blocks made by adapting the CINVA-RAM press with metal cilinders. Before laying the five last courses, the metal rods must be placed in the mortar bed with metal wires around every 30 cm. When placing the bricks, the wires must go through the holes in each row until they are tied around the ring beam. The ring beam should be made with continuous wooden beams as much as possible. Fingerjoints should be used to join different beams together in the strongest possible way.

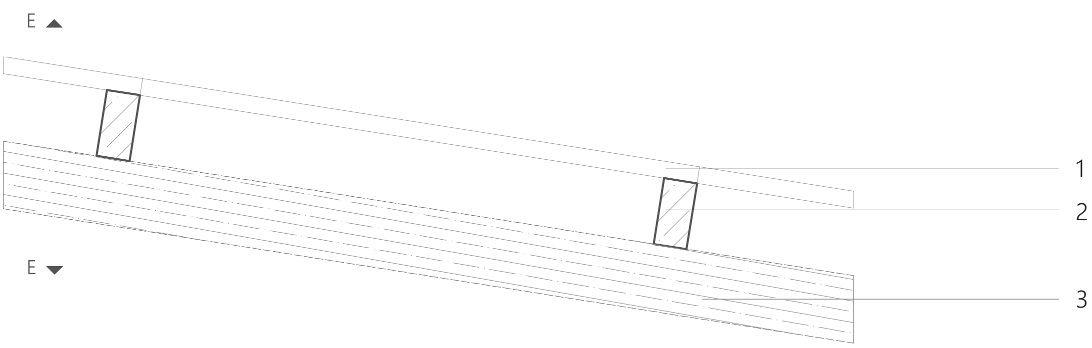

Fig. 6.21 - Component details of the roof R01

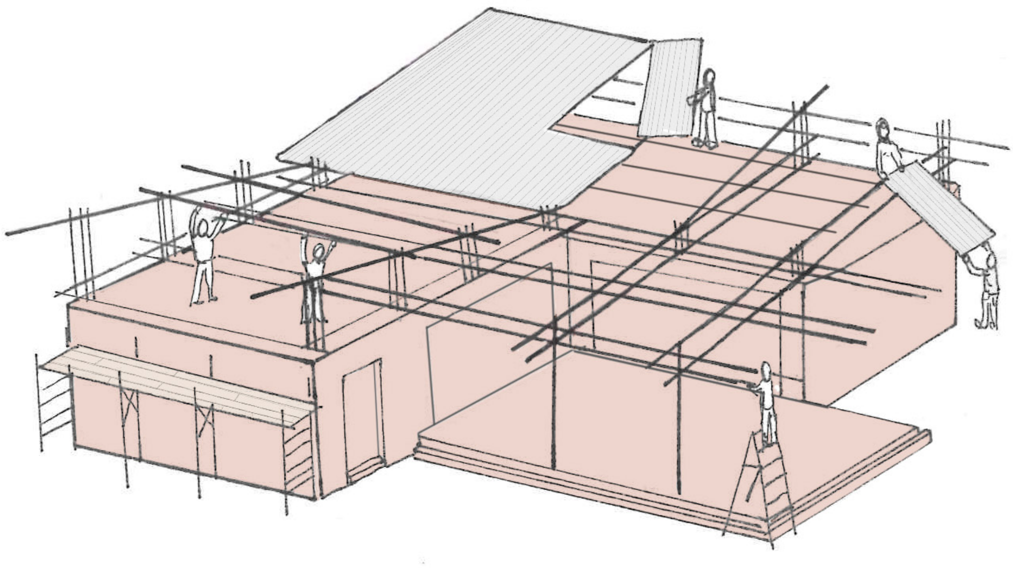

Fig. 6.22 - Schematic drawing of the roof construction process

- **Roof structure**

First, the wooden pillars are assembled by screwing a small piece of wood in between the 6x6 cm poles every meter. These columns can then be attached to the upper ring beam using L-plates and screws. The main rafters are placed sandwiched in the middle of the pillars and are screwed in place. Next, the wood supports are screwed on the rafters.

- **Corrugated metal sheets**

The gutters are placed in the centre supported by the two central rafters, and they are connected to the down pipes on each side. The iron sheets are placed one after the other starting from the bottom row in the centre. Each panel should overlap the others from at least 10 cm. Every screw should be carefully sealed with mastic for waterproofing.

VII. STRUCTURAL DESIGN

VII. STRUCTURAL ANALYSIS

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1. MATERIALS CHARACTERISTICS

In order to conceive a school that is as sustainable as possible, materials have been chosen to be natural or reused as much as possible, if not recyclable materials were prefer.

1.a. Raw earth

- **Choice motivation and use**

Being locally available and having always been used in African vernacular construction, raw earth is the main material of the project. Indeed, it was chosen for structural walls, as filling and for plaster. Moreover, this natural and biocompatible material is an abundant natural resource which use doesn't imply chemical products and complicated processes. Besides, at the end of its life cycle, it can be simply returned to nature without any treatment. Thus, its use benefits both the planet and workers as well as future users of the building.

In order to meet the requirements needed for the different quoted functions, it is used in different forms. First, compressed earth blocks (CEB) are used for the structural walls. Regarding the filling function required above the classrooms' ceiling and the secret rooms and in the floors, light weight earth is used. Finally, walls are covered with clay plaster.

- **Characteristics**

As we didn't get to visit the place and analyse the earth available in Baghere, we assumed that local raw earth is suitable for construction purposes. This assumption is supported by the different construction projects carried out by the association Balouo Salo in Baghere, using local raw earth as a construction material. To produce bricks the proportions are considered to be 65 % of raw earth (clays, silts, sand and gravels) and 35% of sand. [1]

Compressed earth bloc (CEB)

The earth compression with a machine, increases its mechanical resistance and especially its compressive resistance. This is a crucial point as far as raw earth works better in compression than in tension. Thus, compression efforts need to be favoured over tensions in the structural walls. Besides, earth has a great heat storage capacity and can regulate the heat and moisture of the environment. To build raw earth walls, earth mortar is used to link the different brick elements. Finally, compressed earth blocks have a good fire resistance (3 hours - REI 180) and owing to to the clay porosity, sound isolation is also interesting. However, raw earth is sensitive to water, hence the importance of protecting it from the rain with long edged roof and a suitable coating and from the humidity with foundations 50 cm above ground level in waterproof materials, stones for example. [1]

	Symbol	CEB 20	CEB 40	CEB 60
Mechanical characteristics				
Density	ρ	From 1800 kg/m^3 to 2100 kg/m^3		
Average compressive strength	f_{ck}	2 MPa	4 MPa	6 MPa
Average tensile strength	f_{tk}	0,2 MPa	0,4 MPa	0,6 MPa
Young Modulus	E	1,5 GPa	2,5 GPa	4 GPa
Shear (G = 0,4.E)	G	0,6 MPa	1 MPa	1,6 MPa
Shear strength of mansonry	f_{vk0}	0,10 MPa	0,10 MPa	0,10 MPa
Poisson coefficient	ν	0,2	0,25	0,3
Hygrothermal characteristics				
Thermal conductivity		0,8 W(m.K)$^{-1}$		
Thermal capacity (at 20°C)	C	800 J(kg.K)$^{-1}$		
Water vapour permeability	Δ	1,27.10^{-10} kg.(m.s.Pa)$^{-1}$		
Fire reaction	A1 non-combustible			
Fire resistance	3 hours - REI 180			

Tab. 7.1 - CEB Characteristics @Craterre

Earth plaster

Its main function is to protect the earthen walls from the rain. It is made either of loam mortar from earth and lime-casein for water resistant surfaces or clay plaster for protected ones.

Light weight earth

Composed of 48 % of straw to minimise the weight, it plays a role in the classroom isolation from the heat.

Mortar

Load transmission from one brick to another, go through the mortar of the mansory. It is important to have a well done joint to avoid any tension in bricks, especially as raw earth doesn't work well in tension.

1.b. Laterite stones

- **Choice motivation and use**

Laterite stones is a local and natural material suitable and often used for building foundations in the area. It has good mechanical characteristics to fulfil its main functions : carry, stabilised the building, and to keep soil moisture away from earth walls. Thus, its height must be at least 50 cm above ground level.

1.c. Samba wood

- Choice motivation and use

Samba wood, or Ayous wood, is a local hardwood tree that not only grows fast but is also locally available. Besides, its colour is very warm and its combination with raw earth colour offers a nice palette. It has also been chosen for its durability and its good mechanical characteristics. This material ensures a structural function for vertical and horizontal elements in the buildings' systems and is also used for the roof structure.

- Characteristics

Being part of hardwood trees family, this wood has great mechanical properties as descripted in the following table. [2]

	Symbol	Samba wood
Density	ρ	380 kg/m^3
Resistance to bending	$f_{m,k}$	52 MPa
Resistance to compression	$f_{c,0,k}$	30 MPa
Resistance to parallel traction	$f_{t,0,k}$	47 MPa
Resistance to shear strength *	$f_{v,k}$	3,5 MPa
Young Modulus	E	7,26 GPa
Shear Modulus *	G	0,59 GPa

* Due to a lack of information on the wood, some data are based on the table CNR DT 206–R1 / 2018, considering Samba wood as a D18 resistance class wood.

Tab. 7.2 - Samba Wood Characteristics

1.d. Steel

- **Choice motivation and use**

To ensure the ceiling stability, steel IPE beams are used as main beams. It was a necessary solution to support jack-arches ceilings made of raw earth bricks and provide a lighter structure for the structural walls, as well as being aesthetically pleasing. Regarding the project loads, S235 steel will be used in this project.

- **Choice motivation and use**

Generally speaking, the characteristics of steel are particularly noteworthy in terms of tension. The main action to which it is subjected in the ceiling structure is bending. [3]

	Symbol	S235
Density	ρ	7850 kg/m^3
Minimum Yield strength	f_y	235 MPa
Tensile strength	$f_{t,k}$	360 - 510 MPa
Young Modulus	E	210 GPa
Shear Modulus	G	82 GPa
Poisson coefficient	ν	0,28

Tab. 7.3 - S235 Characteristics

2. TECHNIQUES AND PRE-DIMENSIONING

2.a. CEB walls

According to the literature, the most widespread dimensions for BTC are 9 cm x 14 cm x 29,5 cm. To validate these dimensions we first made a pre-sizing based on normative, official documents and models. Among them, the New Mexico State Building Code, Section 2405, were used to pre-dimension structural walls thickness. Indeed, it is one of the few countries which has a Building code for raw earth constructions. Regarding the walls thickness, a minimum of 30 cm for a height of 3,25 m is required. This is equivalent to two courses of standard bricks.

2.b. Jack Arches

Jack arches masonry slab was initially developed for industrial building in Britain in the 80's. Nowadays, it is used for industrial and residential buildings mainly in Europe, in the Middle East, India and in Africa as in different schools projected by Kere architecture which give a new interpretation and form to this system. Jack arches slab consist in a series of small semi-circular vaults, closely-spaced, supported by parallel beams in steel, wood or concrete. The arches are made of raw earth bricks or clay bricks and their rise from 1/10 th of their span. [4][5]

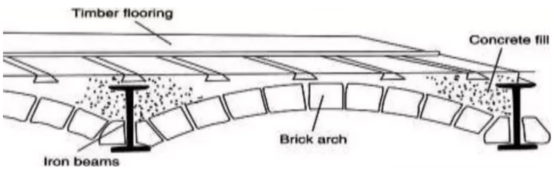


Fig. 7.1 - Jack arches details @krishnakanth

Fig. 7.2 - Jack arches @architecturaldigest

The first Jack arches were known as Victorian jack arches and had larger brick arches of 1.5 m wide with a maximum rise of 20 cm. [6] Then, in the 20th century, arches span were reduced to 80 cm to 1.0 m and their rise were also reduced to 5 cm to create a flat surface with only plastering. Besides, transverse tie-rods tecnique helped in joining the steel beams and providing lateral support for the beams but is no longer used. [7]

In our project, a span of 1.5 m and a rise of 16 cm are used. To flatten the roof, the arches are then covered with a layer of raw earth or concrete. This layer also play a role in the structural resistance of the arches but also increases its isolation. Its thickness needs to be adjusting depending on the material. Regarding the loads transmission, the brick arches transfer it in compression along the arch to the supporting beams and that transfer it to the supporting walls or girders. Owing to its geometry, this system can be considered as a one-way system.

Its main advantages are its capacity to cover wide areas, its material saving and its aesthetic.

2.c. Coffered ceiling

A coffered structure was chosen for the secret rooms ceilings. It is made up of wooden beams fixed to the structural wall. The whole structure is then covered with lightened earth, leaving an opening in the centre to let in more light. The beams are then concealed by the indoor earth covering. Installation is quick and easy.

To pre-dimension the beams, the loads to which the structure is subjected have been evaluated. Then, with predimensioning tables, dimensions have been chosen : 8 cm x 12 cm. They correspond to the smallest ones in tables. These dimensions will then be tested by more detailed calculations and compared with the mechanical properties of the wood.

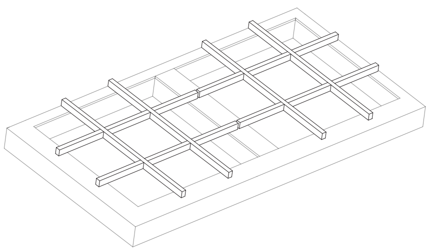


Fig. 7.3 - Coffered ceiling details

3. LOADS ANALYSIS

In order to conduct calculation on structural elements, different parameters need to be settled to determine calculation coefficient. To proceed, the Italian regulation NTC 2018 is used.

3.a. Construction type

The nominal design life V_N of a work is defined as the number of years in which the structure, subject to the necessary maintenance, will maintain specific performance levels. The minimum values of V_N to be adopted for the different types of construction are described in NTC 2018 Table 2.4.I. [8] :

Construction type		Minimum Value V_N (anni)
1	Temporary and provisional constructions	10
2	Constructions with ordinary performance	50
3	Constructions with high performance levels	100

Tab. 7.4 - Construction type classification @NTC 2018

3.b. Use Class

In NTC 2018.2.4.2, based on the use of the building and the consequences of an operational interruption or collapse, constructions are divided into the following classes in Tab 7.5.

3.c. Loads classification

According to NTC 2018.2.5.1, an action is defined as "any cause or set of causes capable of inducing limit states in a structure." Thus, they are classified regarding their type of application (direct, indirect or degrading), the structural response (static, pseudo static or dynamical) and their intensity over time (permanent G, variable Q, exceptional A and seismic E)

For permanent actions, they are subdivided in subclasses regarding their structural functions:
- G1 : own weight of all structural elements
- G2 : own weight of all non-structural elements
- displacements and deformations imposed, including shrinkage
- pre-stress (P)

Regarding variable actions Q, they imply all actions acting instantaneously over time such as :
- overloads due to maintenance for example
- wind actions
- temperature actions
- ...

Classes	Description
Classe I	Occasional presence of people, agricultural constructions
Classe II	Constructions whose use involves normal crowding, without dangerous content for the environment and without public and social functions : - industries with environmentally non-hazardous activities - bridges - infrastructure works - road networks not covered by Use Class III or Use Class IV - railway networks whose disruption does not cause emergency situations - dams the collapse of which does not cause major consequences
Classe III	Constructions whose use involves significant crowding : - industries with environmentally hazardous activities - extra-urban road networks not covered by Class IV use - bridges and railway networks whose disruption causes emergency situations - dams of importance due to the consequences of their possible collapse
Classe IV	Construction with important public or strategic functions, also with reference to civil protection management in the event of disasters

Tab. 7.5 - Building classes classification @NTC 2018

3.d. Geometry and loads

Using the construction details, we can proceed to the calculation of the permanent loads G1 structural and G2 non-structural. The thickness of the materials are indicative and may be modified to meet structural requirements.

Object	Weight
	kg
Window with fixed frame	12,8
Door	14,0

Tab. 7.6 - Permanent loads for windows and doors

Layers	Materials	Thickness	Geometrical Parameters			N °	Density	Weight	Structural	Non-structural
		t [mm]	Name	Value [mm]	Span [m]	U	ρ [kg/m³]	σ [kg/m²]	σ [kg/m²]	σ [kg/m²]
Protective coating	Lime casein stabilizer	40	-	-	-	1	1600	64,0		x
Earth filling	Clay straw lightweight loam	100	-	-	-	1	700	70,0		x
Separation	Straw	5	-	-	-	1	60	0,3		x
Support	Samba wood board	30	-	-	-	1	380	11,4	x	
Structure	Samba Wood beam	120	Width	80	1,5	1	380	45,6	x	
Total									57,0	134,3

	Structural loads	Non-Structural
	G1	G2
Permanent loads [kN/m²]	0,56	1,32
Permanent linear loads [kN/m]	0,15	1,32

Tab. 7.7 - Permanent loads for classroom floor - F01

Layers	Materials	Thickness	Geometrical Parameters			N °	Density	Weight	Structural	Non-structural
		t [mm]	Name	Value [mm²]	Span [m]	U	ρ [kg/m³]	σ [kg/m²]	σ [kg/m²]	σ [kg/m²]
Protective coating	Lime casein stabilizer	40	-	-	-	1	1600	64,0		x
Earth filling	Clay straw lightweight loam	100	-	-	-	1	700	70,0		x
Ceiling	CEB	90	-	-	-	1	1800	162	x	
Structure	IPE 180	Height 180	Area	2395	6,0	1	7850	18,8 kg/m	x	
Total									-	134,0

	Structural loads	Non-Structural
	G1	G2
Permanent loads [kN/m²]	-	1,4
Permanent linear loads [kN/m]	2,8	2,00

Tab. 7.8 - Permanent loads for jack arches - C01

Layers	Materials	Thickness	Geometrical Parameters			N °	Density	Weight	Structural	Non-structural
		t [mm]	Name	Value [mm]	Span m	U	ρ [kg/m³]	σ in [kg/m²]	σ in [kg/m²]	σ in [kg/m²]
Protective coating	Lime casein stabilizer	20	-	-	-	1	1600	32,0		x
Earth filling	Clay straw lightweight loam	100	-	-	-	1	700	70,0		x
Structure	Samba wood beam	120	Width	80	0,9	1	380	45,6	x	
Support	Samba wood board	20	-	-	-	1	380	7,6	x	
Protective coating	Lime casein stabilizer	40	-	-		1	1600	64,0		x
Total									53,2	166,0

	Structural loads	Non-Structural
	G1	G2
Permanent loads [kN/m²]	0,52	1,63
Permanent linear loads [kN/m]	0,10	1,38

Tab. 7.9 - Permanent loads for coffered walls - C02

Layers	Materials	Thickness	Geometrical Parameters			N °	Density	Weight	Structural	Non-structural
		t [mm]	Name	Value [mm]	Span [m]	U	ρ [kg/m³]	σ [kg/m²]	σ [kg/m²]	σ [kg/m²]
Roof	Corrugated iron sheet	0,75	-	-	-	1	-	6,74		x
Structure main beam	Clay straw lightweight loam	120	Width	60	6,0	1,5	380	68,4	x	
Structure support beam	Samba wood	120	Width	60	3,0	1	380	45,6	x	
Secondary beams	Samba wood	80	Width	60	3,0	2	380	60,8		x
Structural pillar	Samba wood	80	Mean Height	1300	-	4	380	29,2	x	
Total									143,2	67,54

	Structural loads	Non-Structural
	G1	G2
Permanent loads [kN]	0,29	0,71

Tab. 7.10 - Permanent loads for roof

Layers	Materials	Thickness	Geometrical Parameters			N °	Density	Weight	Structural	Non-structural
		t [mm]	Name	Value [mm]	Span [m]	U	ρ [kg/m³]	σ [kg/m²]	σ [kg/m²]	σ [kg/m²]
Protective coating	Lime casein stabilizer	20	-	-	-	1	1600	32,0		x
Structure	CEB	295	-	-	-	1	1800	531,0	x	
Protective coating	Lime casein stabilizer	40	-	-	-	1	1600	64,0		x
Total									531,0	166,0

	Structural loads	Non-Structural
	G1	G2
Permanent loads [kN/m²]	5,21	0,94
Permanent linear loads [kN/m]	15,63	2,83

Tab. 7.11 - Permanent loads for walls - W01

- **Variable loads**

Variable loads are related to the use of the structure. They are either concentrated vertical loads q_k, horizontal linear loads H_k or uniformly distributed vertical loads Q_k.Depending on the area of the school, different category get to be considerated : B2 for teachers offices which are not accessible to the public, C1 for the classrooms which are susceptible of crowding and H for roofs accessible for maintenance only.

- *Maintenance*

Maintenance loads are given in NTC 2018, Tab. 3.1.II. and transcribed in the following table :

Categories	q_k [kN/m²]	Q_k [kN]
B – Offices B2 Offices open to the public	2,00	2,00
C - Susceptible crowding area C1 – Areas with tables, such as schools, restaurants, reading and reception	3,00	3,00
H - Accessible roof for maintenance	0,50	1,20

Tab. 7.12 - Variables loads q_k and Q_k @NTC 2018

NB : In the limit states combinations, only the combination with the worst influence on the structure will be taken into account.

- *Wind*

Inclined pitch roofs with wooden structures are widely used in these areas. Indeed, they enable natural ventilation under the roof, its implementation is easy and material are locally available.

However, they have a significant wind surface area, which must be taken into account to prevent the roof from blowing off. Besides, wind also affects the building stability as it exerts a force generally horizontal that can induce dynamic effects on the structure. Thus, in a first place, wind velocity and pressure are calculated. Senegalese standards are used to established wind speed and wind pressure. It had to be compared and completed with the Italian standard CNR-DT 207/2008 to established the wind force responsible of the roof lifting.

Based on Senegalese Standards, Baghere is in zone 2, as shown in Fig. 5.4, which corresponds to a wind pressure q_r = 615 N/m². [9]

To compare and complete the Senegalese standards with Italian standards CNR 207_2008 and NTC 2018, Sedhiou wind data has been compared to Asciano wind data on a yearly basis in Tab. 7.13 and Tab. 7.14. Sedhiou has been chosen as it is the closest and most accurate weather station near Baghere. Thus, calculation can be carried out on the city of Asciano located in Toscana and be reported on Sedhiou data using the report factor linking both data.

Fig. 7.4 - Wind zone according Senegale standards @SENEVENT, NS 02-058

Sedhiou wind data	km/h	m/s
Average wind speed	8,42	2,34
Max wind speed	17,7	4,92
Average gust	21	5,84

Tab. 7.13 - Sedhiou yearly wind data @NOAA

Asciano wind data	km/h	m/s
Average wind speed	7,31	2,04
Max wind speed	14,5	4,03
Average gust	21	5,84

Tab. 7.14 - Asciano yearly wind data @NOAA

Wind comparison determines a factor of 1,22 between maximum wind speed data that will be used to report wind speed found with Italian standard calculation to Sedhiou.

Regarding NTC 2018 3.3, Asciano wind data and parameters are given by :

- Region : Toscana
- City : Asciano
- Height : 11 m
- Zone : Zone 3
- k_s = 0,37
- Reference speed at sea level : $v_{b,0}$ = 27 m/s
- Building altitude above sea level: a_0 = 500 m

From NTC 2018 3.3.1, reference wind speed is calculated as $v_b = C_a * v_{b,0}$,

with :

- C_a = 1 as $a_s < a_0$, the altitude coefficient provided by NTC 2018
- $v_{b,0}$ = 27 m/s , reference speed at sea level

Thus $\mathbf{v_b}$ **= 27 m/s**

Then, from NTC 2018, 3.3.2, the reference speed is calculated as $v_r = v_b * c_r$,

with :

- c_r = 1 , the return coefficient, function of the design return period T_r

Hence $\mathbf{v_r = v_b}$ **= 27 m/s**

Besides, as wind pressures and depressions impact external and internal elements construction, the most critical combination of pressures needs to be determined to calculate the wind stability of the building.

As the project is not a large-scale construction the tangent actions exerted by the wind doesn't have to be taken into account (NTC 2018, § 3.3.4).

According to NTC 2018 §3.3.4, §3.3.5, §3.3.6, §3.3.7 wind pressure is equal to $p = q_r c_e c_p c_d$.

With

- q_r, kinetic reference pressure
  $q_r = \frac{1}{2}\rho v_r^2$, with ρ=1,25 kg/m³ and v_r=27m/s
  q_r = 455,63 N/m² in Asciano
  q_r = 678,16 N/m² in Sedhiou.
  NB : This value is similar to the one given by Senegalese standards.

- c_e, coefficiente di esposizione
  NTC 2018 Tab 3.3.III, Classes of soil : C
  NTC 2018, Fig 3.3.2, Exposition category : III
  k_r = 0,2
  z_0 = 0,10 m
  z_{min} = 5 m
  $z_{Baghere}$ = 15 m
  $c_e(z) = k_r^2 . \ln\left(\frac{z_{min}}{z_0}\right) * c_t(z_{min}) * \left(\ln\left(\frac{z_{min}}{z_0}\right) . c_t(z_{min}) + 7\right)$
  for $z \leq z_{min}$
  thus c_e = 1,70

- c_p =1,13 , pression coefficient [10]

- c_d = 0,95, dynamic coefficient

Thus, taken in consideration the factor between Sedhiou and Ascianowind data, it gives:
$P_{Asciano}$ = 834,96 N/m²
$P_{Sedhiou}$ = 1019,35 N/m²

3.e. Loads combinations

Structural elements must be designed in order to be sustainable over time and continuously satisfy safety standards. Structural verifications are carried out to consider structural limit states during the nominal design life to check if the structure's construction keep meeting the standards requirements. The structural limits states verified from NTC 2018, 2.5.3 are :

- **Ultimate limit states (ULS) :**

Definition : extreme values of action or action effects are taken in consideration to avoid the failure of the structure. The exceeding of an ultimate limit state has an irreversible character.
Combination from NTC 2018 2.5.1 :

$$\gamma_{G_1} \cdot G_1 + \gamma_{G_2} \cdot G_2 + \gamma_p \cdot P + \gamma_{Q_1} \cdot Q_{k_1} + \gamma_{Q_2} \cdot Q_{k_2} \cdot \psi_{02} + \psi_{02} \cdot \gamma_{Q_3} \cdot Q_{k_3} + \dots$$

- **Safety Limit States (SLS) :**

Definition : consideration of the expected behaviour of the structure and its ability to guarantee the expected performance under operating condition. The exceeding of a safety limit state it can be either reversible or irreversible.
Combination from NTC 2018 2.5.3 :

$$G_1 + G_2 + P + \psi_{11} \cdot Q_{k_1} + \psi_{22} \cdot Q_{22} + \psi_{23} \cdot Q_{k_3} + \cdots$$

The values of the coefficients Ψ0j, Ψ1j and Ψ2j are given in Tab. 5.15 and partial safety coefficients γ_{G_i} and γ_{Q_i} are given in Tab. 5.16 :

Environments	Ψ_{0j}	Ψ_{1j}	Ψ_{2j}
B – Offices	0,7	0,5	0,3
C – Area susceptible to crowding	0,7	0,7	0,6
H - Accessible roof for maintenance	0,0	0,0	0,0
Wind	0,6	0,2	0,0

Tab. 7.15 - Combination coefficients @NTC 2018

Type of load	Coeff.		Value
Structural permanent G1	γ_{G_1}	Favourable	1,0
		Unfavourable	1,3
Non-structural permanent G2	γ_{G_2}	Favourable	0,8
		Unfavourable	1,5
Variable Q	γ_Q	Favourable	0,0
		Unfavourable	1,5

Tab. 7.16 - Safety coefficients @NTC 2018

4. DIMENSIONING

4.a. Verification process

In order to dimension each elements and verify their pre-dimensioning made above, a typical classroom will be considered for calculations. ULS and SLS combination will be calculated and then confronted with each material mechanical characteristics.

ULS combinations for loads will be compared with the compressive resistance of the elements as for the CEB walls but also to calculate the bending moments of the elements. The value will then be confronted to the one given by construction standards. For horizontal elements such as steel IPE and wooden beams, considering G1 and G2 linear forces and Qk a punctual forces, maximum bending moment M_{max} is equal to :

$$M_{max} = M_{max,G1} + M_{max,G2} + M_{max,Qk} = \frac{G_1L^2}{8} + \frac{G_2L^2}{8} + \frac{Q_kL}{4}$$

With :

$M_{max,G1}$: Maximum bending moment due to uniformly distributed G_1 loads

$M_{max,G2}$: Maximum bending moment due to uniformly distributed loads G_2

$M_{max,Qk}$: Maximum bending moment due to punctual Q_k loads

L : Length of the structural member

Q_k : Punctual maintenance loads

SLS combination will be used to calculate the deflection of beams using the following formula :

$$\delta_{max} = \delta_{max,G1} + \delta_{max,G2} + \delta_{max,Qk} = \frac{5G_1L^4}{384*EI} + \frac{5G_2L^4}{384*EI} + \frac{QL^3}{48*EI}$$

With :

$\delta_{max,G1}$: Maximum deflection due to uniformly distributed loads G_1

$\delta_{max,G2}$: Maximum deflection due to uniformly distributed loads G_2

δ_{max,Q_k}: Maximum deflection due to punctual loads Q_k

L : Length of an IPE

E : Modulus of elasticity of the beam

I : Inertia moment of the beam

The value will be then confronted to the one given by the constructor.

For wooden beams, the deflection have to take in consideration the viscosity of the wood. This will be described in the corresponding part.

4.b. Classroom floor verifications

The classroom floor is made of wooden beams, resting on filled tyres and supporting different layers. Their dimensions are 8 cm x 12 cm. Thus, in this part, wooden beams have been examined and re-dimensioned when needed, in order to reach the material standards. To execute calcultations Italian normative CNR-DT 207/2008 has been used. Regarding calculations schematisation, it can be associated to a linear element of length L on two supports : one roller and one pinned.

- **Influence zone and loads**

Considering that Samba wood beams of the floor have a spacing of l = 1,0 m, the influence zone width for each beam determines the different loads to take into account :

Structural	Non-structural	Serviciability Loads	
G_1	G_2	q_k	Q_k
[kN/m]	[kN/m]	[kN/m²]	[kN]
0,15	1,32	3	3

Tab. 7.17 - Loads applied on classroom floor

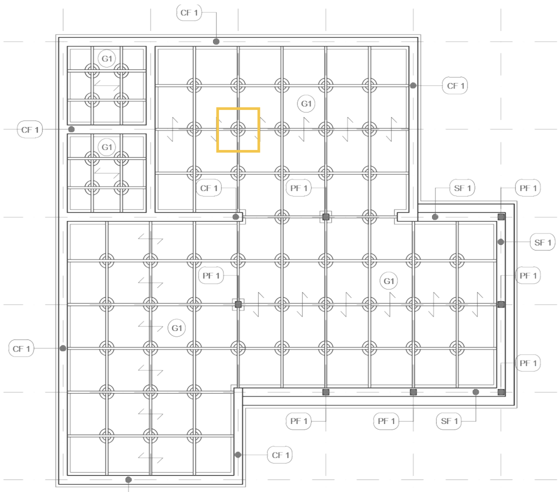


Fig. 7.5 - Influence zone of loads

- **ULS verification**

For ULS combination, the unfavourable coefficients are used :

1. Permanent loads : $1,3 \cdot G_1 + 1,5 \cdot G_2$

2. Short Term loads : $1,3 \cdot G_1 + 1,5 \cdot G_2 + 1,5 \cdot Q_k$

Only the maintenance punctual load Q_k is taken into consideration as it is more detrimental to the structure than the linear loads q_K .

To verify these wooden elements, these two ULS combinations need to be confronted with $k_{mod,\ short\ term}$ and $k_{mod,\ permanent}$ in order to choose between these two coefficients. ($k_{mod,\ short\ term}$ = 0,9 and $k_{mod,\ permanent}$ = 0,6)

Thus as $\frac{ULS_{short\ term}}{ULS_{permanent}} > \frac{kmod_{short\ term}}{kmod_{permanent}}$, $k_{mod,\ short\ term}$ will be retained.

Besides, γ_M = 1,5 corresponding to a continuous production need to be taken in consideration for the verifications.

Finally, to take into account the impact of viscosity, the coefficient k_{def} = 0,8 is used, as the floor is considered to be in Category 2 in CNR DT 206-RI / 2018 , Table 7-2 – Service Class.

Type of loads	Loads		Bending moments		Maximum bending moment
	Uniform loads	Punctual loads	M unif loads	M punct loads	
	[kN/m]	[kN]	[kN.m]	[kN.m]	[kN.m]
Permanent	2,17	0,00	0,27	0,00	0,27
Short term	2,17	4,50	0,27	1,13	1,40

Tab. 7.18 - Maximum bending moment on classroom floor beam

The bending moment enables to calculate :

$$\sigma_{my\_Permanent} = \frac{M_{Ed}}{W} = \frac{M_{Ed}}{\left(b.\frac{h^2}{6}\right)}$$

that will be compared with :

$$f_{myd} = \frac{f_{m,k}}{\gamma_M} * k_{mod}$$

Bending verifications		
f_{myd}	31,20	MPa
$\sigma_{my\_Permanent}$	1,41	MPa
$\sigma_{my\_Short\ term}$	7,27	Mpa

Tab. 7.19 - Bending verification on classroom floor beam

As $f_{myd} > \sigma_{my}$, the use of 8 cm x 12 cm beams at ULS is verified.

- **SLS verification**

For SLS combination, the unfavourable coefficients are used :
1. Permanent loads : $G_1 + G_2$

2. Short Term loads : $G_1 + G_2 + 0,7 . q_k$

Only the distributed maintenance load q_k is taken in consideration as it is more detrimental to the structure than the punctual load Q_k.

Regarding the deflection of the beam the calculations are the following for wooden elements :

$$w_{fin} = w_{ist} + w_{creep}$$

With $w_{ist} = w_{ist}(G) + w_{ist}(Q)$

- $w_{ist}(G) = \frac{5}{384} * \frac{(G_1+G_2)*L^4}{E.I} + \frac{\chi.(G_1+G_2).L^2}{G.A}$
- $w_{ist}(Q) = \frac{5}{384} * \frac{(q_k)*L^2}{E.I} + \frac{\chi.(q_k).L^2}{G.A}$

And $w_{creep} = w_{creep}(G) + w_{creep}(Q)$, due to viscosity

- $w_{creep}(G) = k\_def * f_{ist}(G)$
- $w_{creep}(Q) = 0$

As $w_{ist} < \frac{L}{300}$ and $w_{fin} < \frac{L}{250}$, floor beams are also verified for SLS loads combinations.

4.c. Jack arches verifications

Jack arches are supported by IPE 180 beams made of S235. In order to confirm its dimension, we consider an IPE in a single classroom as far as a class modulus is representative of the other rooms regarding dimensions and loads. Each beams are 5,6 m long and are spaced of l = 1,5 m. Thus, the influence zone width for each beam determines the different loads to take into account :

- **Influence zone and loads**

Considering that IPE beams have a spacing of l = 1,5 m, the influence zone width for each beam determines the different loads to take into account:

Structural	Non-structural	Serviciability Loads	
G_1	G_2	q_k	Q_k
[kN/m]	[kN/m]	[kN/m²]	[kN]
2,8	2,00	0,5	1,2

Tab. 7.21 - Loads applied on IPE

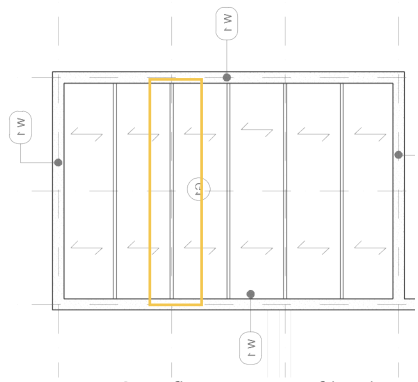


Fig. 7.6 - Influence zone of loads

Type of loads	Loads	w_{ist}	w_{creep}	Total Deflection	Upper limits for vertical displacements		
	[kN/m]	mm	mm	mm	General cover (a)		L / a (mm)
Permanent	1,47	0,82	0,66	3,17	for w_{fin}	250	4,0
Short term	3,57	1,69	0		for w_{ist}	300	3,33

Tab. 7.20 - Vertical displacements of classroom floor beam

	Symbol	S235
Linear Weight	*w*	18,8 kg/m
Inertia	I_{xx}	$1{,}32.10^7$ mm^4
Young Modulus	E	210 GPa
Design elastic bending moment resistance	$M_{el,Rd,yy}$	34,39 kN.m

Tab. 7.22 - Mechanical characteristics of IPE 180 [11]

Regarding the schematisation of the IPE for structural calculations, it can be associated to linear element of length L on two supports.

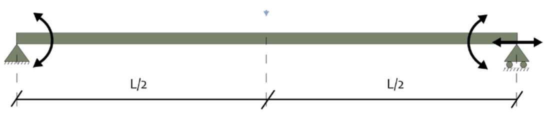


Fig. 7.7 - Static diagram of the system studied

On this element different loads are applied :

- its own weight uniformly distributed and the other structural elements G1
- the weight created by non-structural elements G2
- the service linear load q_k
  In ULS, only the distributed maintenance load q_k is taken in consideration as it is more detrimental to the structure than the punctual load.

- **ULS verification**

For ULS combination, the unfavourable coefficients are used :

1. Permanent loads : $1{,}3 . G_1 + 1{,}5 . G_2$
2. Short Term loads : $1{,}3 . G_1 + 1{,}5 . G_2 + 1{,}5 . Q_k$

Type of loads	Loads	Bending moments
	[kN/m]	[kN.m]
Permanent	6,78	26,58
Short term	7,91	30,99

Tab. 7.23 - Maximun bending moment of IPE 180

The bending moment is then compared with the Design elastic bending moment resistance in Tab. 7.24

Profile	Design elastic Bending Moment Resistance $M_{el,Rd,y}$
	[kN.m]
IPE 160	25,54
IPE 180	34,39
IPE 200	45,66

Tab. 7.24 - Design Bending Moment resistances for IPE

As $M_{max} < M_{el,Rd,y}$, IPE 180 is structurally sustainable as far as ULS is concerned. It seems to have a margin regarding the design elastic bending moment resistance but an IPE 160 couldn't be chosen regarding SLS combination that were not satisfied.

- **SLS verification**

For SLS combination, the unfavourable coefficients are used :

1. Permanent loads : $G_1 + G_2$
2. Short Term loads : $G_1 + G_2 + \Psi_{1,1} . q_k$

The deflection of the beam is calculated as described in §V.4.a :

Type of loads	δ_{max}	Upper limits for vertical displacements	
	mm	General cover a (mm)	L/a (mm)
Permanent	22,24	250	22,4
		200	28,0

Tab. 7.25 - Vertical displacements of IPE 180

The upper limits for vertical displacements are given by NTC 2018 Tab 4.2.XII, taking into consideration the structural elements classification: " General coverage ".

As $\delta_{max} < L/200$, IPE 180 beam is also verified for SLS loads combinations.

4.d. Coffered ceiling verifications

Coffered ceilings in the secret rooms are made of a wooden structure resting on the structural walls. The beams dimensions are 8 cm x 12 cm. Thus this part, wooden beams will be examined and re-dimensioned if needed, in order to reach the material standards.

- **Influence zone and loads**

Considering that Samba woods beams of the ceiling have a spacing of l = 0,90 cm, the influence zone width for each beam determine sthe different loads to take into account :

Structural	Non-structural	Serviciability Loads	
G_1	G_2	q_k	Q_k
[kN/m]	[kN/m]	[kN/m²]	[kN]
0,1	1,47	0,5	1,2

Tab. 7.26 - Loads applied on IPE

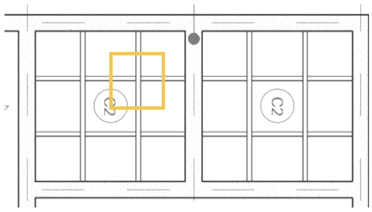


FIg. 7.8 - Influence zone of loads

- **ULS verification**

For ULS combination, the unfavourable coefficients are used :
1. Permanent loads : 1,3 . G_1 + 1,5 . G_2

2. Short Term loads : 1,3 . G_1 + 1,5 . G_2 + 1,5 . Q_k

Only the maintenance punctual load Q_k is taken in consideration as it is more detrimental to the structure than the distributed load q_k.

As verification are made on wooden elements, these two ULS combination need to be confronted with $k_{mod,\ short\ term}$ and $k_{mod,\ permanent}$ in order to choose between these two coefficients. ($k_{mod,\ short\ term}$ = 0,9 and $k_{mod,\ permanent}$ = 0,6)

Thus as $\frac{ULS_{short\ term}}{ULS_{permanent}} > \frac{kmod_{short\ term}}{kmod_{permanent}}$, $k_{mod,\ short\ term}$ will be retained.

Besides, γ_M = 1,50 and k_{def} = 0,8 as the ceiling is considered to be in Category 2 in CNR DT 206-RI / 2018 , Table 7-2 – Service Class.

The bending moment is calculated in Tab. 7.27 and enables to find :

$\sigma_{my\_Permanent} = \frac{M_{Ed}}{W} = \frac{M_{Ed}}{\left(b.\frac{h^2}{6}\right)}$ that will be compared with $f_{myd} = \frac{f_{m,k}}{\gamma_M} * k_{mod}$

Bending verifications		
f_{myd}	31,20	MPa
$\sigma_{my\_Permanent}$	1,17	MPa
$\sigma_{my\_Short\ term}$	3,27	Mpa

Tab. 7.28 - Bending verification on classroom floor beam

As $f_{myd} > \sigma_{my}$, the use of 8 cm x 12 cm beams at ULS is verified.

- **SLS verification**

For SLS combination, the unfavourable coefficients are used :
1. Permanent loads : G_1 + G_2

2. Short Term loads : G_1 + G_2 + $\Psi_{1,1}$. q_k

The deflection of the beam is calculated as described in §V.4.a in Tab 7.29 :

Type of loads	Loads		Bending moments		Maximum bending moment
	Uniform loads	Punctual loads	M unif loads	M punct loads	
	[kN/m]	[kN]	[kN.m]	[kN.m]	[kN.m]
Permanent	2,34	0,00	0,24	0,00	0,24
Short term	2,34	1,80	0,24	0,41	0,65

Tab. 7.27 - Maximum bending moment on coffered beam

Type of loads	Loads	w_{ist}	w_{creep}	Total Deflection	Upper limits for vertical displacements		
	[kN/m]	mm	mm	mm	General cover (a)		L / a (mm)
Permanent	1,48	0,44	0,40	0,99	for w_{fin}	250	3,6
Short term	0,5	0,15	0		for w_{ist}	300	3,0

Tab. 7.29 - Vertical displacements of coffered ceiling beam

As $w_{ist} < \frac{L}{300}$ and $w_{fin} < \frac{L}{250}$, floor beams are also verified for SLS loads combinations.

4.e. Walls verifications

To ensure the structural stability of vertical elements, we will study the ones subjected to maximum loads. As explain in §V.1.a, the structural walls are made of raw earth CEB bricks, assembled with earth mortar according to Flemish bond pattern. Their bonding enhances their structural capacity under compression and shear forces. Moreover, it also induces the transfer of horizontal loads through adhesion between mortar and earth bricks, hence the importance to have a full layer of mortar under each earth block otherwise, peak stresses can be created in blocks. The CEB brick dimensions are 29,5 x 14 x 9 cm given by the standards. [1]

- **Influence zone and loads**

In the project, two critical facades have to be studied :
- The external façade of a classroom with six windows
- The internal façade of the cafeteria, with three consecutive opening of 3 m span each separated by wooden pillars

- Classroom façade

It is interesting to study it as it contains six openings that will induce a different loads repartition than for full walls. They are grouped by two spaced by 60 cm and 1,2 m separate each group of windows. More precisely, in the classroom façade three raw earths portions have to be studied carefully :

- Wall in compression at the feet of the wall, submitted to its own weight and to the load implied by the ceiling and the roof

- Wall in compression of raw earth between two windows

- Walls in compression directly subjected to G_1s loads.

- **ULS verification**

For ULS combination, the unfavourable coefficients are used :

1. Permanent loads : 1,3 . G_1 + 1,5 . G_2

2. Short Term loads : 1,3 . G_1 + 1,5 . G_2 + 1,5 . Q_k

NB :Only the maintenance punctual loads Q_k is taken in consideration as it is more detrimental to the structure than loads q_k.

In order to have more precise results, loads and the structural system have been put into the software Dlublal RFEM. The results can then be confronted with the mechanical characteristics of raw earth listed in §V.1.a.

Permanent Loads			Serviciability Loads	
$G_{1,wall}$	$G_{1,ceiling}$	$G_{1,roof}$	q_k	Q_k
[kN/m]	[kN]	[kN]	[kN/m²]	[kN]
13,02	2,9	0,54	0,5	1,2

Tab. 7.30 - Loads applied on raw earth wall

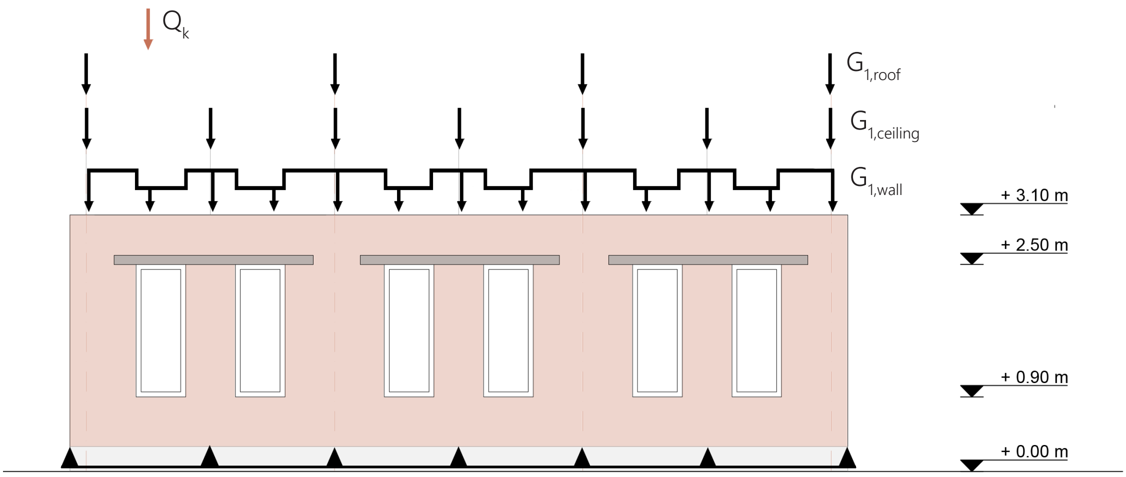


Fig. 7.9 - Loads applied on raw earth wall

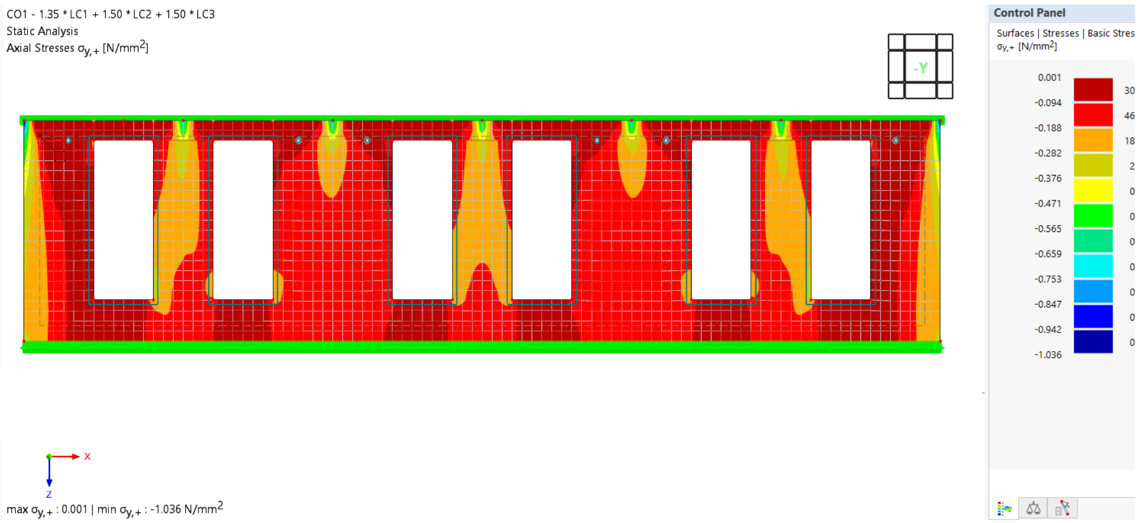


Fig. 7.10 - Compressive stresses in raw earth walls

Wall position	$\sigma_{c,max}$ [MPa]
Feet of the wall	0,188
Between two windows	0,282
Directly submitted to G_{1s}	0,753

Tab. 7.31 - Software simulation results

The corner of the walls will not be taken in to consideration in the analysis of the result as the simulation doesn't consider the attachement of the studied facade to the others structural walls.

Regarding ULS verification for compressive stress, we compared it to the compressive strength design value, f_{cd}. To do so, Eurocode 6 in masonry was used as no standards for raw earth could be accessed. Thus, we assumed to have a class C material. To verify the structure we have to be in class 3 regarding the availability of appropriately qualified and experienced personnel employed by the contractor, for supervision of the work. Hence, γ_M=2,5 and $f_{c,d}$=0,800 MPa. [12]

As $f_{cd} > \sigma_{max,}$ walls compression is validated at ULS.

Material		γ_M Class 1	2	3	4	5
	Masonry made with:					
A	Units of Category I, designed mortar[a]	1,5	1,7	2,0	2,2	2,5
B	Units of Category I, prescribed mortar[b]	1,7	2,0	2,2	2,5	2,7
C	Units of Category II, any mortar[a, b, e]	2,0	2,2	2,5	2,7	3,0

a Requirements for designed mortars are given in EN 998-2 and EN 1996-2.

b Requirements for prescribed mortars are given in EN 998-2 and EN 1996-2.

c Declared values are mean values.

d Damp proof courses are assumed to be covered by masonry γ_M.

e When the coefficient of variation for Category II units is not greater than 25 %.

Fig 7.11 - Eurocode 6 for Mansory, γ_M @Eurocode 6

4.f. Cafeteria beams verifications

The cafeteria lintels above doors are made of Samba wood and rest on wooden pillars. Their dimensions are 12 cm x 22 cm and they have a span of 3 m hence its examination to confirm or not that it can reach the material standards.

- **Influence zone and loads**

The influence zone is the surface above the beam, which loads are considered uniformly distributed or punctual as shown in Fig. 5.9.

To check the beam dimensions the process is the same as in §V.4.d and it has been put into the structural simulation software Dlublal RFEM in order to have more precise results.

- **ULS verification**

For ULS combination, the unfavourable coefficients are used :

1. Permanent loads : $1{,}3 \cdot G_1 + 1{,}5 \cdot G_2$

2. Short Term loads : $1{,}3 \cdot G_1 + 1{,}5 \cdot G_2 + 1{,}5 \cdot Q_k$

Only the maintenance punctual load Q_k is taken into consideration as it is more detrimental to the structure than the linear loads q_K and it is placed in the worst position regarding the structure stability.

Maximum values of tensile stress and shear stress will be compared to the design value of the wood f_{md} and f_{vd}. Results shown in Fig 7.11 and Fig. 7.12 are transcribed in Tab. 7.31 :

Simulation results and resistance values	Value [MPa]
$\sigma_{m,max}$	9,671
f_{md}	31,20
τ_{max}	0,878
f_{vd}	2,10

Tab. 7.33 - Software verifications for the beam

As $f_{md} > \sigma_{m,max}$ and $f_{vd} > \tau_{max}$ beams dimension for the cafeteria are confirmed at ULS.

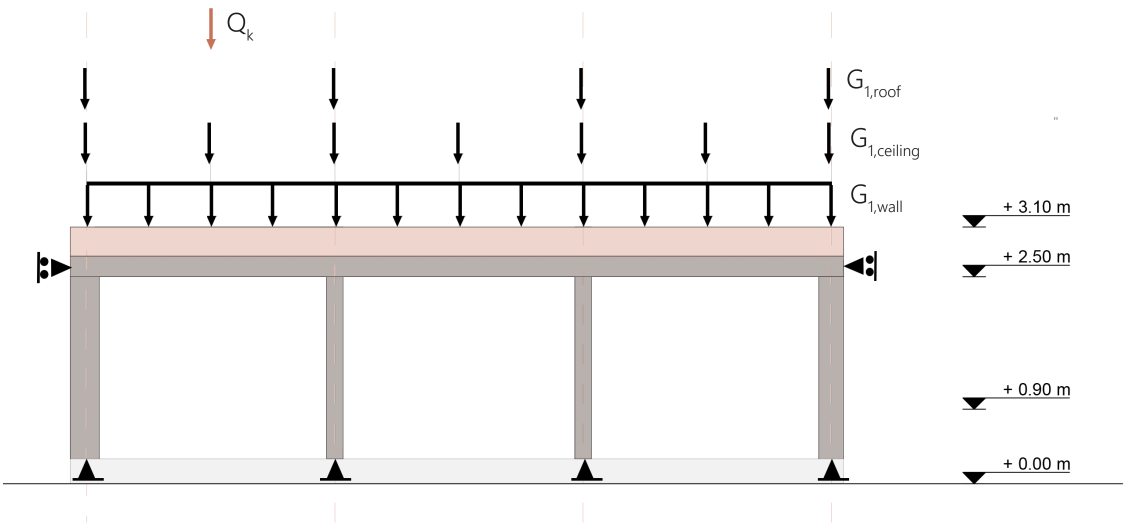


FIg. 7.12 - Loads applied on raw earth wall

	Permanent Loads				Serviciability Loads	
	$G_{1\ walls}$	$G_{1\ beams}$	$G_{1\ Ceiling}$	$G_{1\ roof}$	q_K	Q_k
	[kN/m]	[kN/m]	[kN]	[kN]	[kN/m²]	[kN]
	1,56	0,10	14,4	1,00	0,5	1,2

Tab. 7.32 - Loads applied on cafeteria beam

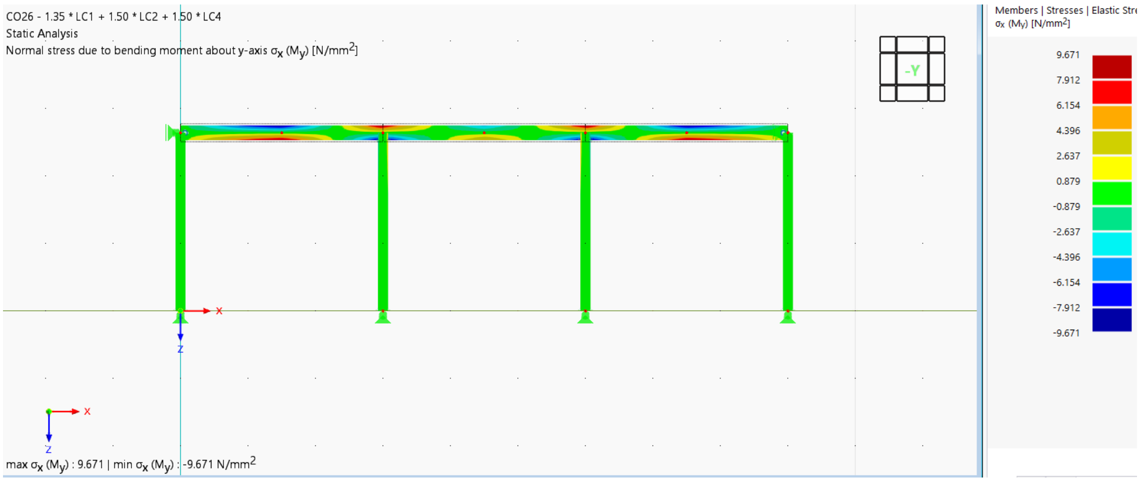


Fig. 7.13 - Bending stresses in the cafeteria beam

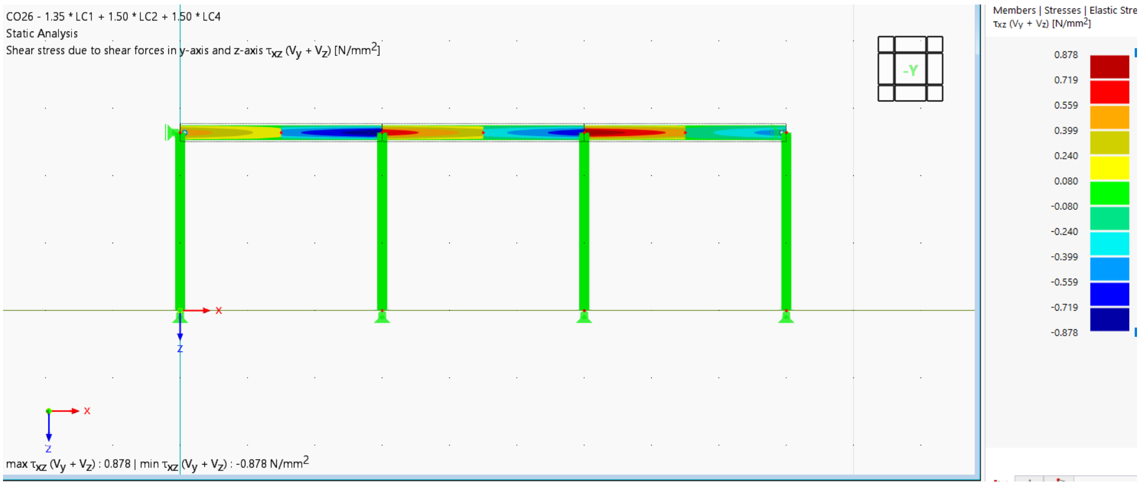


Fig. 7.14 - Shear stresses in the cafeteria beam

- **SLS verification**

For SLS combination, the unfavourable coefficients are used :

1. Permanent loads : $G_1 + G_2$
2. Short Term loads : $G_1 + G_2 + \Psi_{1,1} \cdot q_k$

In Fig. 5.12, results show that $\delta_{max} = 3{,}9$ mm.

The vertical deflection limit for a wooden beam is given by L/200 which corresponds 12 mm.

As $\delta_{max} < L/200$, cafeteria beam dimensions are also verified for SLS loads combinations.

4.g. Windows lintel verifications

The windows' lintels are made of Samba wood and are supported by the structural walls. Their dimensions are 7 cm x 29,5 cm x 30 cm. Indeed, a unique lintel for each group of two window was chosen as the windows are separated of 60 cm and the lintel had to exceed of 30 cm around the windows according to earth buildings guidelines. Its examination will confirm or not if it can reach the material standards.

- **Influence zone and loads**

The influence zone is the surface above the window lintel, which load is considered uniformly distributed or punctual as shown in Fig. 7.7.

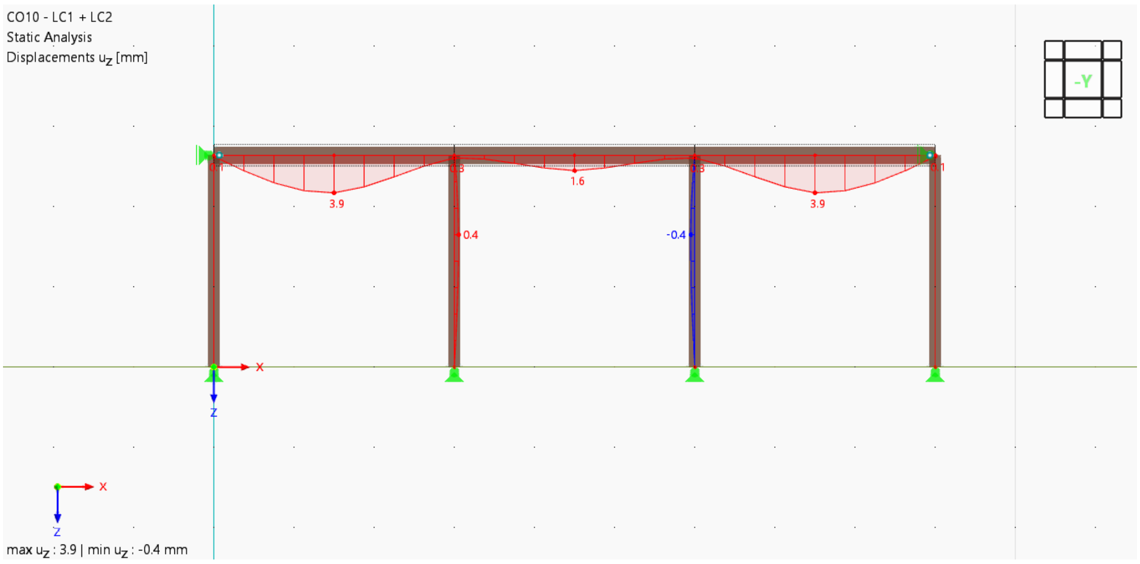


Fig. 7.15 - Vertical displacement of the cafeteria beam

	Permanent Loads			Serviciability Loads	
$G_{1\ walls}$	$G_{1\ beams}$	$G_{1\ Ceiling}$	$G_{1\ roof}$	q_K	Q_k
[kN/m]	[kN/m]	[kN]	[kN]	[kN/m²]	[kN]
2,08	0,08	14,4	1,00	0,5	1,2

Tab. 7.34 - Loads applied on window lintel

The process is the same as in §V.4.d and has been put into the structural software RFEM in order to have more precise results.

- **ULS verification**

For ULS combination, the unfavourable coefficients are used :

1. Permanent loads : 1,3 . G1 + 1,5 . G2
2. Short Term loads : 1,3 . G1 + 1,5 . G2 + 1,5 . Q_k

Only the maintenance punctual load Q_k is taken into consideration as it is more detrimental to the structure than the distributed load q_K.

Simulation results and resistance values	Value [MPa]
$\sigma_{m,max}$	3,361
f_{md}	31,20
τ_{max}	0,052
f_{vd}	2,10

Tab. 7.35 - Software verifications for the window lintel

Maximum values of tensile stress and shear stress will be compared to the design value of the woof f_{md} and f_{vd}. Results shown in Fig. 7.11 and Fig. 7.12 are transcribed in Tab. 7.35.

As $f_{md} > \sigma_{m,max}$ and $f_{vd} > \tau_{max}$ beams dimension for the cafeteria are confirmed at ULS.

- **SLS verification**

For SLS combination, the unfavourable coefficients are used :

1. Permanent loads : $G_1 + G_2$
2. Short Term loads : $G_1 + G_2 + \Psi_{1,1} . q_k$

In Fig. 5.13, results show that δ_{max}= 0,3 mm.

The vertical deflection limit for a wooden beam is given by L/250 which corresponds 2,4 mm.

As δ_{max} < L/200 , cafeteria beam dimensions are also verified for SLS loads combinations.

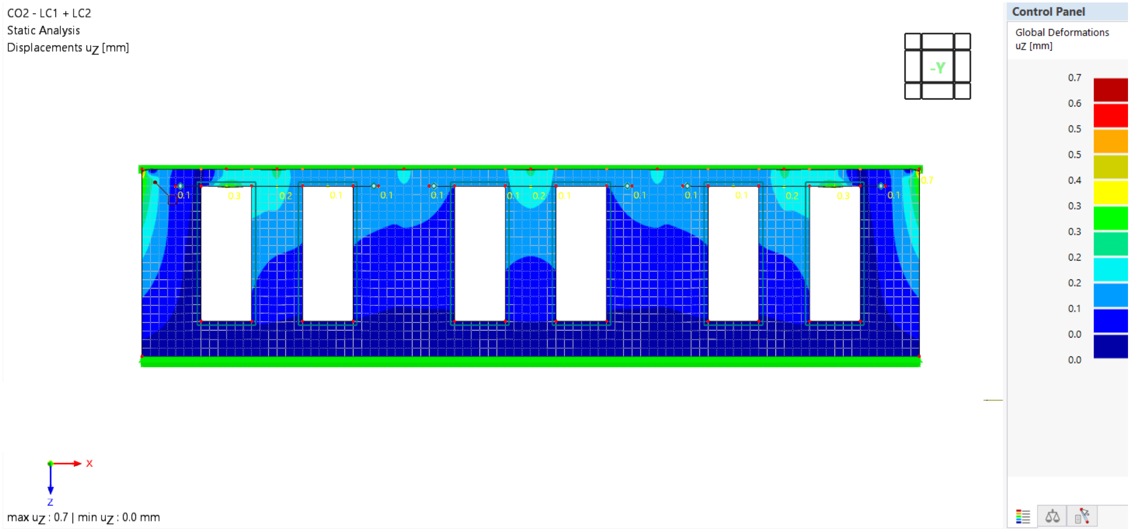


Fig. 7.16 - Vertical displacement of the windows lintels

4.h. Column buckling verifications

The pillar supporting the beam in the cafeteria zone could be subjected to buckling. Indeed not only the beam loads is supported by the pillar but also are a part of wall, ceiling and roof too. Its dimensions are 15 cm x 15 cm.

- **Influence zone and loads**

The influence zone is the surface above it, which loads are considered uniformly distributed or punctual :

Permanent loads			Service Loads
$G_{1,walls}$	$G_{1,IPE}$	$G_{1,roof}$	Q_k
[kN]	[kN]	[kN]	[kN]
9,83	14,4	1,0	1,2

Tab. 7.36 - Loads applied on the column

The pillar can be assimilated to a column on a pinned support and linked to the other element with a roller support. Knowing this, the effective length can be calculated for buckling calculation verification as in Fig. 7.17. [13]

- **ULS verification**

For ULS combination, the unfavourable coefficients are used :

1. Permanent loads : 1,3 . G1 + 1,5 . G2
2. Short Term loads : 1,3 . G1 + 1,5 . G2 + 1,5 . Q_k

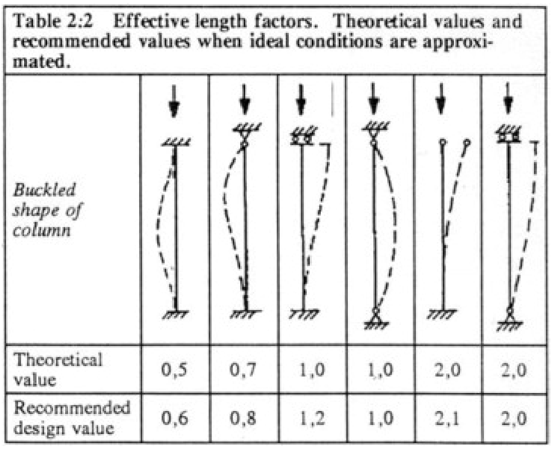


Table 2:2 Effective length factors. Theoretical values and recommended values when ideal conditions are approximated.

Buckled shape of column						
Theoretical value	0,5	0,7	1,0	1,0	2,0	2,0
Recommended design value	0,6	0,8	1,2	1,0	2,1	2,0

Fig. 7.17 - Effective length @Handbook of Offshore Engineering

Only the maintenance punctual load Q_k is taken into consideration as it is more detrimental to the structure than the distributed load q_k.

Type of loads	Loads
	[kN]
Permanent	34,06
Short term	35,86

Tab. 7.37 - ULS combination applied to the pillar

Compression	
f_{c0d}	18 Mpa
$\sigma_{c//perm}$	1,514 Mpa
$\sigma_{c//short}$	1,594 Mpa

Tab. 7.38 - Compression stresses

Knowing the compression acting on the columns, buckling verification can be carried out using the following coefficient :

L_{eff}	2200 mm
ρ	0,04 mm
λ	50,81
$E_{5\%}$ *	6,11 GPa
$\lambda_{rel,c}$	1,13
k	1,22 > 0,3
$k_{crit,c}$	0,59
$f_{c,0,d}$	18,00 MPa
Limite f_{c0d} x k_{crit}	10,64 MPa
$\sigma_{c\ short}/(k_{crit}*f_{c0d})$	0,15 < 1
$\sigma_{c\ perm}/(kcrit*f_{c0d})$	0,14 < 1

* E 5% was calculated based on the report of E and E 5% of a D18 wood.

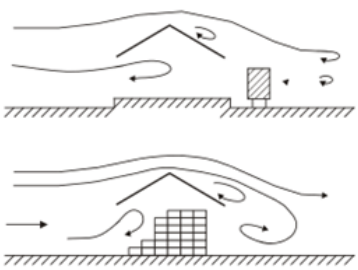
Tab. 7.39 - Buckling calculation

As $\sigma_{c\ perm}/(kcrit*f_{c0d})$ and $\sigma_{c\ short}/(k_{crit}*f_{c0d})$ are inferior to 1, the pillar is not subjected to a detrimental buckling that could cause the instability of the structure.

4.i. Wind verifications

As the roof pitch is subjected to lifting due to wind action, wind resulting force needs to be calculated and compared with the structural loads. All the calculation were done using the Italian standards CNR-DT 207/2008. [14]

Roof without obstruction, φ=0



Roof with obstructions, φ=1

Fig. 7.18 - Difference of air flow for roof with φ=0 and φ=1 @CNR-DT 207/2008

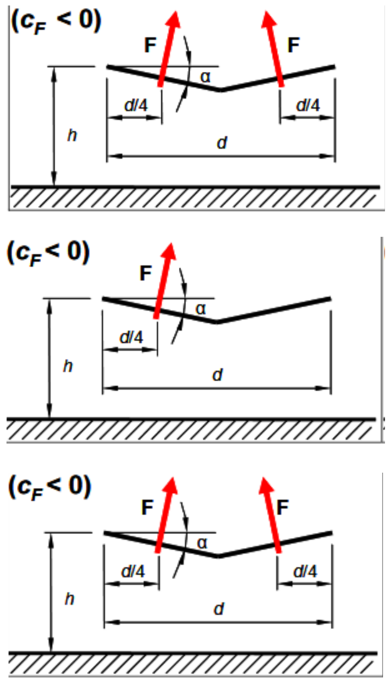


Fig. 7.19 - Position of the wind force application @CNR-DT 207/2008

As explained in Italian standards and through the Fig. 7.15 and Fig.7.16 wind flow will create a force on the roof that can cause the lifting of the roof as:

$$F = q_p * \bar{z} * L^2 * c_F$$

With :

- q_p = 1157,96 N/m² , the wind peak pressure
- z = 102,72 m² , the roof surface
- c_F = - 0,68, the force coefficient calculated with TableG.XIII of CNR-DT 207/2008 where φ = 1 and α = 9 °

Hence, **F = 80,88 kN**

To compare this force with our structure load we will assume that this load is distributed equally in each column supporting the roof. Thus in each beam a tension force of F = 12,34 is exerted by the wind.

Taking into consideration all structural elements and dividing by the number of columns, the punctual structure load in each column can be thus compared to the punctual loads induced by the wind.

Conclusion : to avoid any roof lifting, the roof structure must be hooked to the IPE beams.

NB : All these assumptions were made with standards that are applicable for Italian areas. Thus, even though a report between wind speed was taken into account, these standards may not be well adapted to the local climate and may also be oversized for the Senegalese environment.

Loads counterbalancing wind action [kN]	
Corrugated roof	0,05
Wood columns	0,56
Wood roof strcuture	1,13
Brick ring	3,52
Wooden ring beam	0,49
IPE	7,75
Ceiling	85,44
Total structure	98,93
Total per column	12,37
Wind Force	12,34

Tab. 7.40 - Loads counterbalancing wind action

Other solutions to counteract wind force could be to decrease the roof angle. This was not done in our case for two reasons: First, regarding the area of the roof, 9° is the minimum angle to collect properly the water and secondly decreasing the angle would make us loose the symbolic character of the roofs as explained in the architectural part §II.3.

Finally another solution could be to cover the area underneath the roof to prevent the wind from blowing under the roof.


@Adobe Stock

VIII. PASSIVE DESIGN

VIII. PASSIVE DESIGN

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Passive design can be defined as the characteristic of a building whose architectural features take advantage of local climatic resources to provide a comfortable indoor environment, while reducing the energy consumption regarding lighting, mechanical ventilation, heating, or cooling. Bioclimatic architecture is another term first introduced in 1963 by Olgyay and developed by Givoni in 1969. It characterizes a building integrated in the cycles of nature, able to use of them as a strentgh without causing damages. [1] To create passive architecture, the designers should integrate the thought of natural elements into every step of the design process. The shape, the orientation, the disposition, the materials, and the openings of the building determine the indoor environment created. The passive strategies are especially important in a context like rural Senegal, where the climate can be extreme, and the energy supply is unreliable. It is therefore crucial to design an autonomous building which shelters its users from the outside heat and humidity.

1. TROPICAL CLIMATE CHARACTERISTICS

1.a. Climate analysis

The very first step of bioclimatic design is the study of the climatic conditions. No extensive climate database was found for Baghere, so the database used as reference is the NOAA's Integrated Surface Database for Kolda from 2007-2021. Kolda is situated in the same climatic zone, 60 km to the East. It is also in proximity with the Casamance river and inland. The proximity of Ziguinchor to the coast made it less comparable to the climate of Baghere. We still must consider the differences between Kolda and Baghere during the solutions design : the latter is a small village surrounded by forests and fields whereas Kolda is a bigger city. Moreover, the Casamance river is much larger near Baghere, which could result in higher humidity rates.

As already introduced in the context analysis in part I, Casamance climate is tropical, hot, and humid with a season of intense rain concentrated in summer.

- **Temperatures**

The air temperatures are rather high all year long in Kolda, varying on average from 25°C to 32°C, for an annual mean of 28,4°C. We should still consider that the urban heat island effect could be taking place in Kolda, and therefore the temperature in Baghere could be slightly inferior. Other factors influencing the local temperature are the surfaces which colour and texture can reflect solar radiation. This is highlighted in the measure of the albedo, developed in the daylight analysis.

As seen in Fig. 8.1, during the annual average day, the temperature varies from 15°C, in the middle of the night, to 35°C, in the middle of the afternoon. This 10-degrees difference can be used with the strategies of thermal mass. We can also notice that humidity is lower during the day. It must be managed properly during nighttime.

- **Humidity**

Relative humidity is the ratio of water vapour contained in the air. It is high in this tropical region varying on average between 40 and 85%. Locally, the factors that can increase this parameter are the vegetation, and the proximity with Casamance river. The humidity levels can lead to a different perceived temperature and to discomfort from a moist sensation to a dry sensation.

- **Rain**

The rain season takes place in the summer and lasts approximately four months long. Intense rains happen almost every day during this period. No rainfall is observed during the rest of the year while the air and soil becomes progressively drier.

- **Wind**

The wind in the region can be described in three seasons, with different directions and speeds. Knowing the main wind directions is useful to design a building to make the most of natural ventilation and avoid draught sensation. In Baghere, the wind comes from the South-Sest from March to May, from the South and South-West from June to November and from the North-East in the winter. We therefore mainly observe one South-Sest to North-East axis along which the wind blows one way or the other

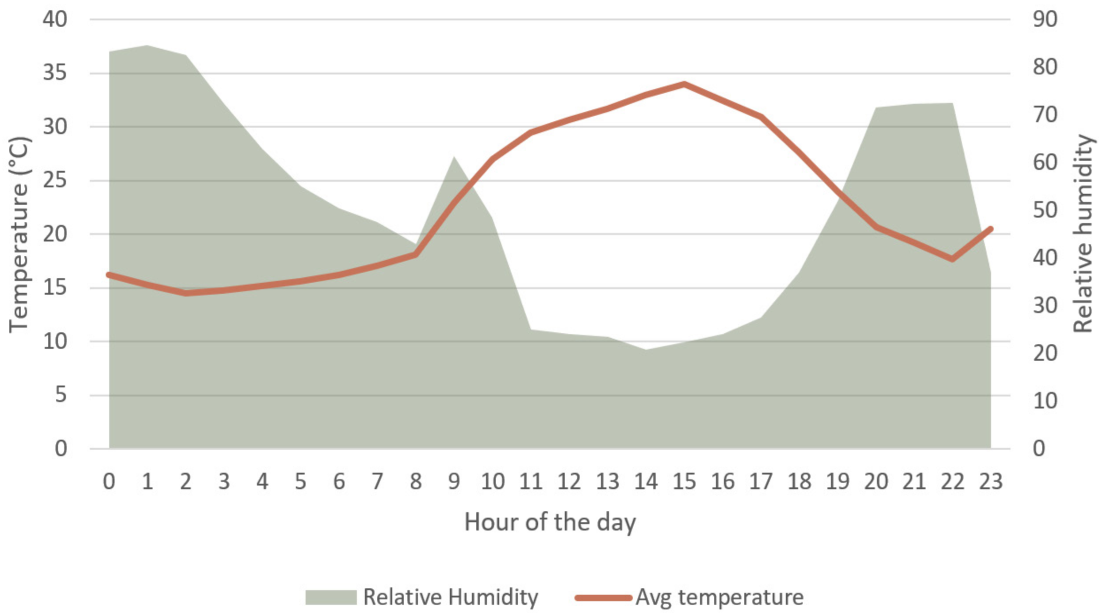

Fig. 8.1 - Average weather conditions during the day in Kolda @NOAA

during the year. Locally, the river can also induced small breezes. In our case they would come from the South. The low building density of the area should not affect greatly the direction and speed of the wind on our plot. However, the vegetation planted around the buildings can reduce locally the wind force received on the buildings. The wind speed doesn't vary much during the year, on average between 1,3 and 2,6 m/s.

In Baghere, being quite close to the Equator, the sun is in the South most of the year, and in the North in the summer. We can also understand that the sun is rather high in the sky in the middle of the day all year long. Therefore, the North and South façades will not receive much direct sunlight, whereas the East and West façade are much more exposed to sunlight, respectively in the morning and in the evening. Therefore, they are the façades to which the most attention should be dedicated when designing solar protection.

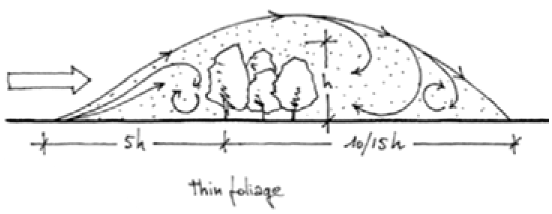

Fig. 8.2 - Effect of vegetation on local wind @UN-HABITAT

- **Sunlight**

The solar diagram allows us to understand the relative paths of the sun, and thus the direction of the sunrays, at a given date and time. The polar diagram is a projection of the relative positions of the sun on a plan. The further the point is from the center, the lower the sun. The position of the curve about the centre shows in what direction the sun is.

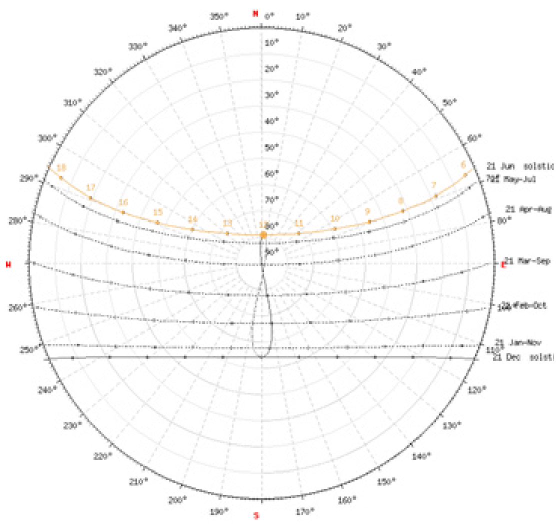

Fig. 8.3 - Solar diagram for Baghere, Senegal @SolarSunPath

Solar radiation is the measure of the solar energy received on a surface. It has both incidence on the temperature and the light. Many factors come into play for the calculation of the local solar radiation. The geographic location, slope, orientation, season, and time of the day all impact the solar radiation. The local parameters that may change the global radiation found in the database can be the shaded obstructions found in and around the project (buildings, vegetation, roof overhangs...) and the proximity with the Casamance river, which is sometimes a sea inlet, and as such can create clouds of water vapour. Besides, the saltiness can also change locally the atmospheric composition. [1]

- **Challenges**

The problematics of the climate of Baghere are multiple:

- Humidity, although useful for the vegetation, can also damage structures and favour the proliferation of mould. This tropical climate also promotes the proliferation of insects such as mosquitoes which can be vectors of diseases. These consequences must be kept in mind during the construction details design.

- The intense summer rain season implies some design choices to protect the buildings and avoid floodings. It is also an opportunity to collect and store rainwater for hygiene and gardening purposes to be used during the dry season.

- The important solar radiation can be at the origin of glare in the building, preventing focus on learning tasks. An adequate orientation of the buildings and a well thought-out design of the openings are required to obtain the minimum acceptable levels of lighting for scholastic premises. A study of the daylight inside the main rooms has been developed for this purpose.

- High temperatures and humidity can create discomfort. The next step is therefore to study the thermal comfort in the area and find solutions to make buildings shelters from the harsh tropical climate, using passive solutions.

1.b. Thermal comfort and bioclimatic charts

Thermal comfort is a complex notion. It is normally measured by experiment with a sample of people rating their comfort level in a given place. From this experimental data, different models have been developed to estimate the comfort level from various factors. The physical factors that have been found to influence the thermal comfort are the following:

- The temperatures of the air and the surfaces surrounding the space. The temperature of comfort is usually found between 18°C and 26°C depending on the activity and clothes of the users. Too much temperature difference between surfaces can create a discomfort by radiation asymmetry.

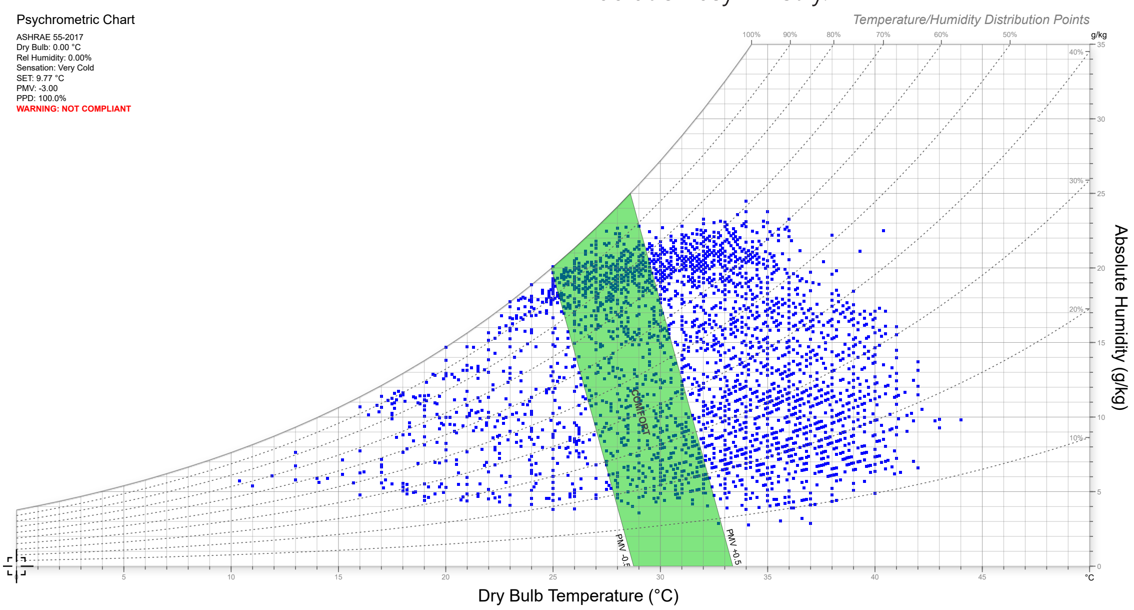

Fig. 8.4 - Psychrometric chart of the ASHRAE 55 comfort levels for hourly datapoints in Kolda, Senegal

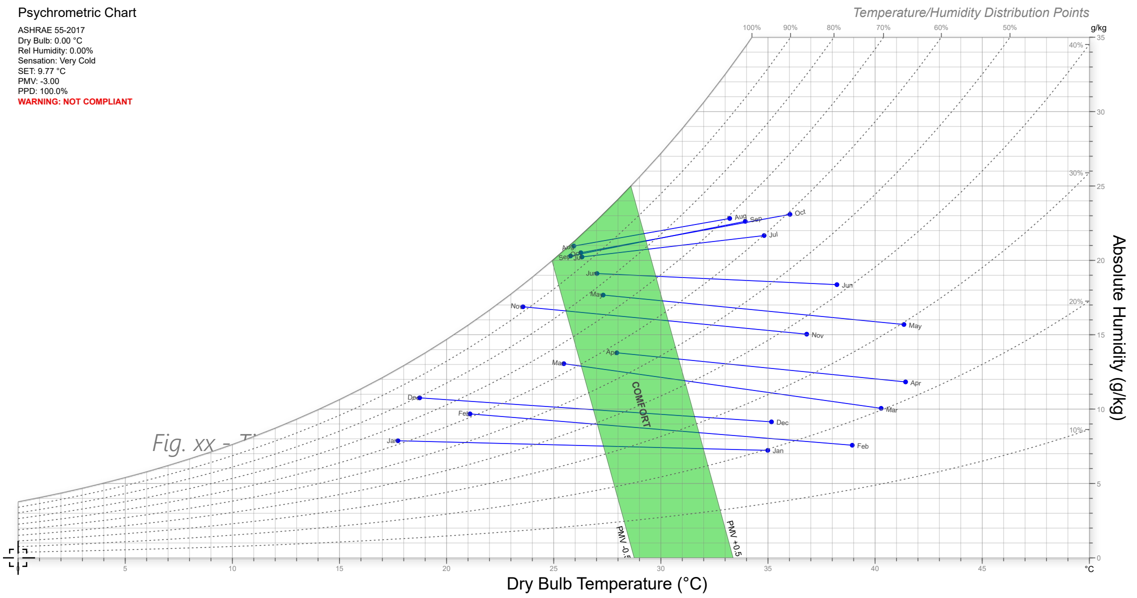

Fig. 8.5 - Psychrometric chart of the ASHRAE 55 comfort levels for monthly ranges in Kolda, Senegal

- The air humidity. Indeed, the general comfort zone is rather broad: between 30-70% of relative humidity an take in consideration temperatures.

- The wind speed. Air currents can create discomfort when the air speed exceeds 0,2 m/s.

Many other factors have been proven to influence the thermal comfort, which is far from being a purely physical variable. First and foremost, the activity and clothing of the user has a tremendous impact on the level of comforts. Then some psychological factors come into play and are much harder to calculate. For example, stress reduces the resistance to heat. One's mood also influences its perception of the temperature. The colours and furnishing of the space can alone change the perceived thermal comfort with the same physical parameters. [2]

Different models offer an estimation of the comfort zone :

- **Psychrometric models**

The first is the Fanger model, developed in the 1970s, considering the three physical parameters mentionned above, as well as the clothing and activity of the users. On this basis, it measures a Predicted Mean Vote (PMV) between -3 and 3, 0 being for neutral sensation. The comfort zone is usually considered for an optimal PMV between -0.5 and 0.5. The European norm EN ISO 7730 was built based on this model.

In the beginning of the 2000s, the Fanger model is found to be accurate from air-conditioned buildings but inappropriate for naturally ventilated buildings. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) develops new adaptive models to consider the adaptation of the individual to its environment. The ASHRAE 55 standard is first published in 2004 and adapts the comfort zone depending on the average monthly exterior temperature. The European norm EN 15251 of 2007 uses this adaptive model as basis. [2]

From the ASHRAE 55 psychrometric charts in Fig 8.4 and 8.5, we can see how the external climate is mostly too hot for the thermal comfort of users, except during the winter. It must be noted that people from warm climatic zones were found to have a higher tolerance to heat than the ASHRAE standards. [3] Some hourly data are also found to be under the comfort levels mostly in winter.

- **Givoni chart**

The Givoni chart was developed in the 1969 based on the Olgyay's diagram, which considers ambient temperature and humidity, mean radiant temperature, wind speed, solar radiation, and evaporative cooling. As well as defining the comfort zone, the Givoni chart also suggests adaptive design strategies based on the outdoor climatic conditions. [1]

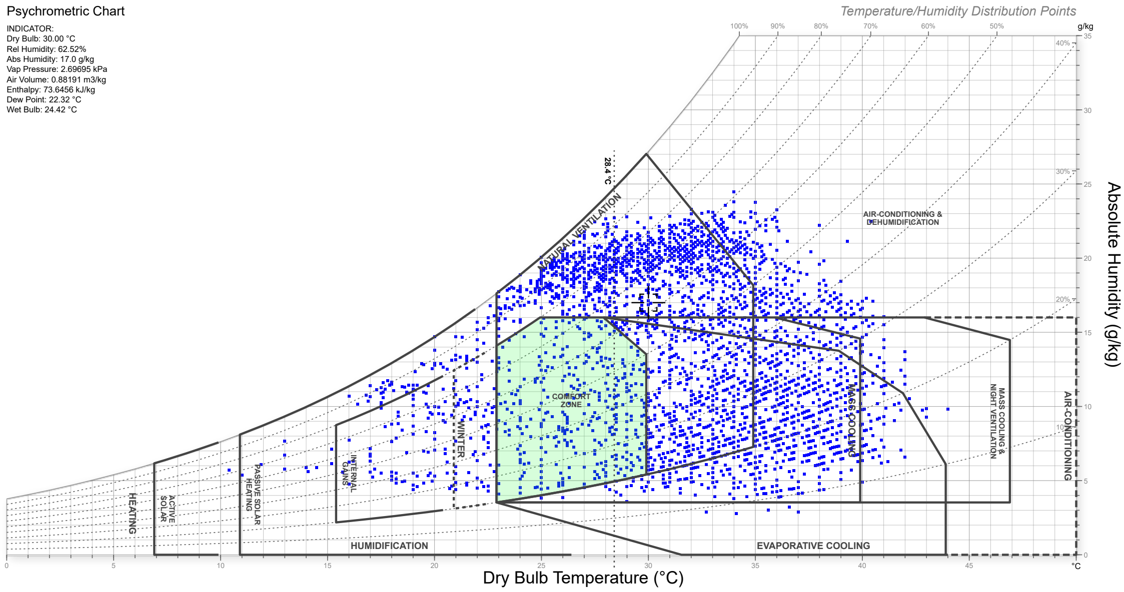

Fig. 8.6 - Givoni chart for Kolda, Senegal, hourly datapoints all year long from 8am to 6pm

As observed in Fig. 8.6, the hourly datapoints for Kolda fall mostly into four categories: comfort zone, natural ventilation, mass cooling and evaporative cooling.

Natural ventilation is useful when the humidity is too high. It concentrates the most datapoints for Kolda. According to Givoni, the maximum acceptable air speed indoors is 2 m/s, which limits the effectiveness of ventilation for temperatures above 32°C. [1]

Mass cooling is useful for higher temperature with lower humidity. This strategy consists in using massive materials with high thermal inertia for the building envelope, to allow the building to store heat during the day and release it during the night when the temperatures decrease. It can be combined with night ventilation to dissipate the stored heat more efficiently.

Evaporative cooling reduces the air temperature by water evaporation. This technique also increases the humidity, and the ventilation should be studied to avoid water vapour accumulation. In our case, this solution seems less appropriate but could be used along other strategies.

These three passive strategies have been used in vernacular architecture which can serve as inspiration for our project. Along with this strategies, solar protection to diminish heat gains is also important in a tropical climate.

2. VERNACULAR SOLUTIONS FOR TROPICAL CLIMATES

2.a. Natural ventilation

Natural ventilation is the utmost priority in hot and humid climates. It helps reducing humidity and cooling spaces at the same time. Design principles should be applied since the very beginning of the architectural project to ensure a pleasant indoor environment.

- **Masterplan**

The first step in using natural ventilation arrived as soon as the design starts. Indeed, the building plots and footprints will directly influence the effectivness of natural ventilation. The surrounding areas and obstacles modify and determine a great part of the local wind on the plot. Having buildings in proximity could shield the construction from the wind and compromise available natural ventilation. In a hot and humid climate, the urban form often shows buildings in staggered patterns, fairly far apart from each other, with wide streets. This pattern allows direct exposition to predominant winds from each building. The buildings should be spaced at a distance of seven times their height if facing each other; closer if staggered. The optimal orientation of the street would be 20° - 30° oblique to predominant wind. Obviously, the orientation and position of the buildings and the street also serve purposes of access and social relationships, and it should be weighed in the design process.

Green borders of vegetation can be used to cool incoming hot breezes. Planted area can indeed be up to 5 - 8°C cooler than built areas. Waterbodies can have the same effect, cooling the air temperature. However, it may also increase humidity in the air.

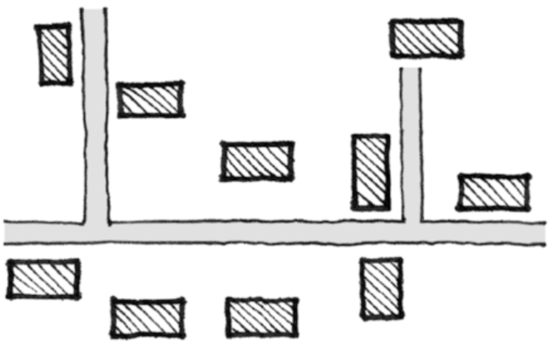

Fig. 8.7 - Typical settlement for hot-humid region @UN-HABITAT

- **Building shape**

The overall building shape, its volume, size, orientation, and openings have a major impact on the effectiveness of natural ventilation. To facilitate ventilation a long and narrow shape is to be favoured over square volume to be well crossed by airflows. Many vernacular buildings, traditional or modern are single-banked, allowing each room to be crossed by a stream of fresh air. For larger buildings, and especially in crowded areas, a courtyard can allow each room to get direct air, so that the ascending wind from the courtyard benefits each user. Multi-storey apartment also experiences better ventilation as the wind speed increases with the height above ground. Domed and vaulted roofs also increase the speed of the air flowing over their curved surfaces, enhancing natural ventilation. They also create a space for the hot air to gather over the users and therefore offer a more comfortable environment at floor level.

The building orientation is also of interest to benefits from the predominant wind. The longer façades should indeed face the direction of the wind, for it to travel the shortest distance across the building. In areas where the wind speed is too high for comfort, a strategy can be to position the buildings so one of its angles faces the wind. This way, the wind will not penetrate directly in the building, but will be deviated and the air entering through the openings will have a reduced speed.

While designing the internal plan of the building, some strategic choices can be made to favour ventilation in the spaces that need it most. For example, the spaces with computers or mechanical systems, subject to internal thermal gains, or the sanitary spaces that require sufficient ventilation could be placed along the façade most exposed to the wind. Open plans also simplify the ventilation inside of the spaces, and if divisions are need for privacy, they should when possible be small or have appropriate openings.

Of course, a major parameter of the internal natural ventilation is the openings. Their position, size, shape, and possible solar protection all have a great impact on the airflow. Different solutions exist to enhance natural ventilation of a building.

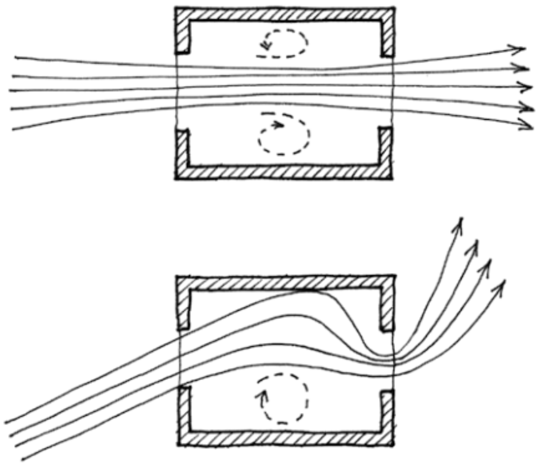

Fig. 8.8 - Effect of the orientaiton of the building on the natural ventilation @UN-HABITAT

- **Solutions for natural ventilation**

The solutions are based on two main airflow drivers: the stack effect and the wind. The stack effect is driven by temperature differences. The cold air entering a building is progressively heated up. Warm air has a lower density, which means that as the air gets hotter, it will also rise up. Due to the stack effect, openings at different heights in the building will create air movement, even with no initial air speed. To enhance the flow rate, the height difference between inlets and outlets can be increased. Another strategy can be to increment the temperature difference between the inside and the outside. This concept is the key mechanism of the solar chimney. The wind can also be the driver of the airflow, if channelled correctly into the building. The solutions can be categorized into these main mechanisms:

- Mono exposed ventilation

Mono exposed ventilation consists of one or more openings on the same side of the building. The air entering can be due to the wind but its movement inside the room is due to the stack effect. This solution is only acceptable for narrow buildings and does not create an important airflow. In the case of an opening directly facing the wind, the wind velocity in the room will be about 10% of the outdoor wind speed in the first fifth of the room width. Hence the depth of the room should not exceed twice its height. The opening should also be tall enough to drive movement.

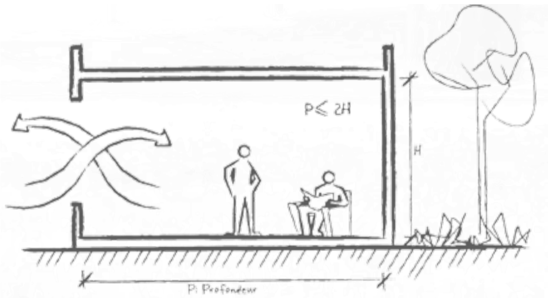

Fig. 8.9 - Mono-exposed ventilation @CSTB

- Cross ventilation

Cross ventilation lets the air travel across the building. For a better efficiency it should usually be implemented with openings on the longer façades, so that the air crosses the building transversally. This solution is more efficient that mono exposed buildings. To increase its efficiency, the openings can be placed at different heights to benefit from the stack effect. The building can also be oriented to benefit from the predominant wind. Finally, this method is especially effective in narrow and even single banked buildings. The maximum depth is five times the height of the room.

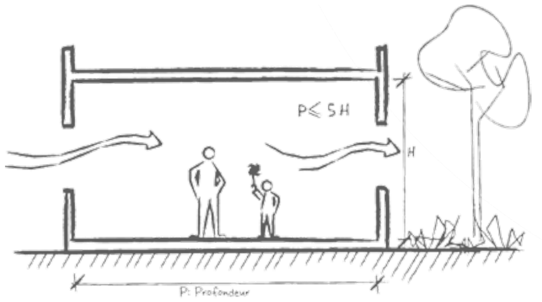

Fig. 8.10 - Cross ventilation @CSTB

Cross ventilation has been used in local buildings, especially in colonial constructions. Many colonial schools have indeed been built in a single-banked narrow floor plan, with a veranda connecting all the classrooms. This allows every room to be crossed by natural ventilation.

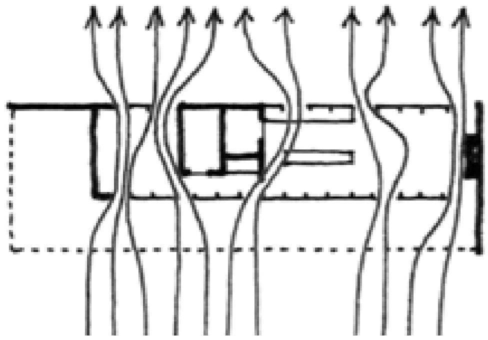

Fig. 8.11 - Cross ventilation in a standard colonial building plan @UN-HABITAT

- Wind catcher

The wind catcher uses the driving force of the wind to create natural ventilation. It serves in cases where openings receiving the prevalent wind cannot be implemented. It is mainly used in high density settlements where the building's façades do not get direct exposition to the wind, or when the most appropriate orientation for wind are in conflict with the sun exposition. The solution consists of a tower that rises above the building bringing in the external air owing to the effect of the wind. Besides, the wind force also increases with the altitude, benefitting this solution. The inlet should be at least 2.4 meters above the height of surrounding obstacles to avoid the layers of turbulences and drags. It should be used on sites where the wind has a fairly high consistent speed.

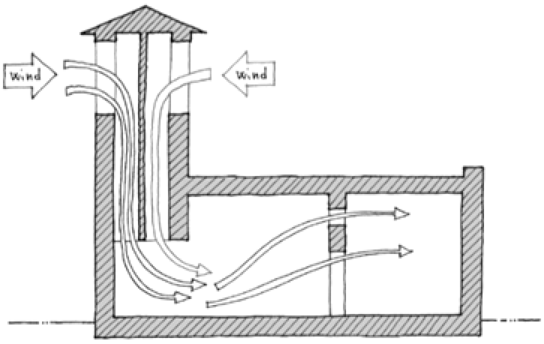

Fig. 8.12 - Wind catcher diagram @UN-HABITAT

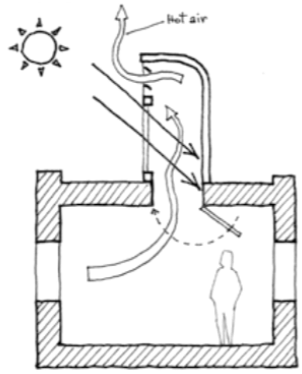

Fig. 8.14 - Solar chimney diagram @UN-HABITAT

In vernacular architecture, the wind catchers take different shapes depending on local wind conditions and local customs. They can face one or more directions and be decorated or simply functional. It is mainly developed in hot arid climate, and vernacular solutions are widespread in Egypt, Pakistan, and Iran.

Fig. 8.13 - Wind catchers in Yazd, Iran @Shervin Abdolhamidi

- Solar chimney

The solar chimney uses the stack effect as main driver for airflow. It is an enhanced cross-ventilation solution. It is especially appropriate in areas with low wind speed. The air enters from the lateral openings and escapes through the solar chimney. The air should be hotter in the solar chimney, designed to be heated up by the sun. The higher the thermal difference between the air in the chimney and in the room, the more important gets the stack effect. To increase the efficiency of the solution, the chimney can be placed on the side most exposed to solar radiation and coated with dark colors or made of glass. It should also be insulated in places where the climate gets colder during the year, to avoid inverted airflow. To benefit from the wind, the chimney outlet can be placed in a depression area. [4] This solution has been used and developed in the Middle East and Near East. It is now also implemented in modern buildings where the wind is not consistent enough to be used in natural ventilation. The Schorge Lycée by Kere architecture in Burkina Faso uses solar chimneys to evacuate hot air from the classrooms. Their position highlight its function of evacuating the air rather than capturing it from the exterior.

Fig. 8.15 - Solar chimneys on the Lycée Schorge by Kere architecture @I.Baan

- Courtyard

A design made with a courtyard can have multiple benefits under a tropical climate. As well as creating social outside space respecting the local customs, it can serve as well a role in ventilation and thermal comfort. The courtyard being shaded during the day can store the cool air for the night. By stack effect, the fresh air will be distributed into the rooms. Moreover, the ground in the courtyard has high thermal mass, and therefore can store heat during the day and distribute it in the night as seen in Fig. 8.14.

This solution is mainly used in hot-arid climate, such as the North of Africa, where it is traditional. It is especially useful when the wind brings dust. The ventilation coming from the courtyard is reversely clean. This building form also favours shading.

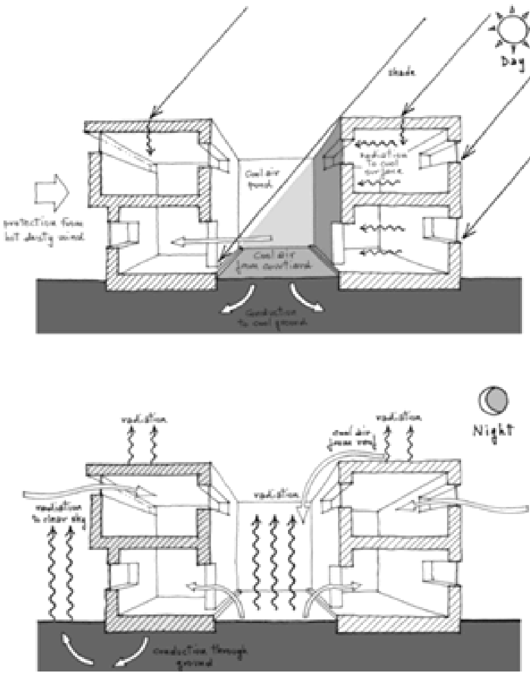

Fig. 8.16 - Passive mechanisms of a centre courtyard @UN-HABITAT

- Overhangs and wing walls

Some morphologic solutions can be added to better direct the wind into the buildings. Placing a horizontal overhang over the opening leads the airflow upwards and can therefore serve in cases where the wind speed is rather high and could be uncomfortable for the users.

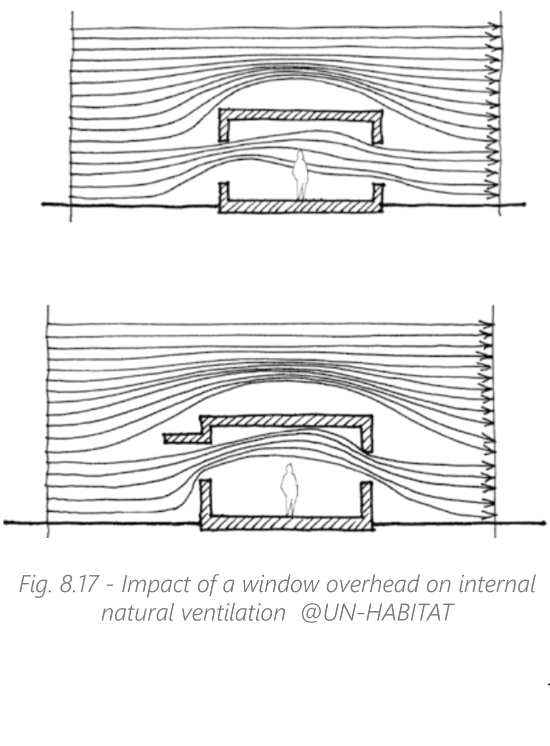

Fig. 8.17 - Impact of a window overhead on internal natural ventilation @UN-HABITAT

In the case of openings on adjacent walls, wing walls can help direct the airflow significantly. They can also increase airflow in a mono exposed room. Louvres, flyscreens and shutters can in the same way have an effect on the airflow in the room and should therefore be taken into account when dimensioning the openings for natural ventilation.

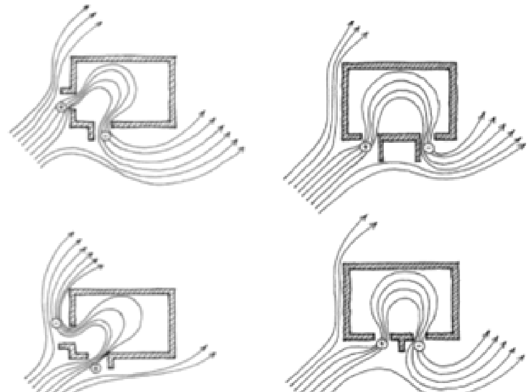

Fig. 8.18 - Effect of wing walls on the internal airflow @UN-HABITAT

- Ventilated roof

The double roof is the most effective roof type for all tropical climates. Its aim is to limit solar gains through the roof. The outer skin should be made of a reflective material such as aluminium sheet, or other light coloured waterproof material. This upper layer shades the inner layer, and reflects part of the solar radiation. The space between roof and ceiling should be ventilated, to evacuate the heat that can be increased by as much as 3°C in the case of metallic upper skin. The openings for roof ventilation should be oriented to benefit from the wind and the outlet should be larger than the inlet. Finally, the inner skin should be insulating. For maximum efficiency they should also be placed at different heights. A reflective surface placed under the roof can also reduce solar gains.

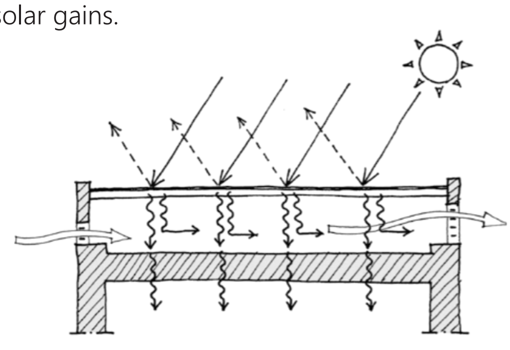

Fig. 8.19 - Double roof diagram @UN-HABITAT

One example is the traditional diola impluvium, in which the houses have a flat earthen ceiling further covered by a large thatch roof. The straw blocks out the rain and the interstice between the two roofs is ventilated. The earthen roof has thermal mass to further limit heat gains in the room. This technique is also used in more modern construction, such as the Dano High School designed by Kere architecture.

Fig. 8.20 - Double roof in Dano High School @Kere architecture

- Ventilated wall

Double-skinned wall can help to reduce heat gains and is particularly recommended for hot-arid climates. Just like the double roof, its efficiency grows with the reflectiveness of the outer layer. The air trapped between the two layers flows from the bottom to the top of the wall, evacuating heat. Usually, the outer lead is made of bricks, concrete, or panels. To store freshness, the inner layer should have an appropriate thermal mass as stone, concrete or raw earth wheraeas hollow blocks should be avoided.

2.b. Thermal mass

To get across a wall, heat can take more or less time depending on the characteristics of the materials. This phase shift is generally linked to the density of the material. Thus, in a first approach massive walls, ceilings and floors have a high thermal mass.

This characteristic allows the building envelope to store heat during the day and release it in the night when the temperature decreases. Moreover, the wall cooled down in the night will remain cool during most parts of the day. The solution can further be enhanced by introducing night ventilation and cooling down the building effectively. The result will be a dephasing and reduction of the inside temperature in comparison to the outdoor conditions.

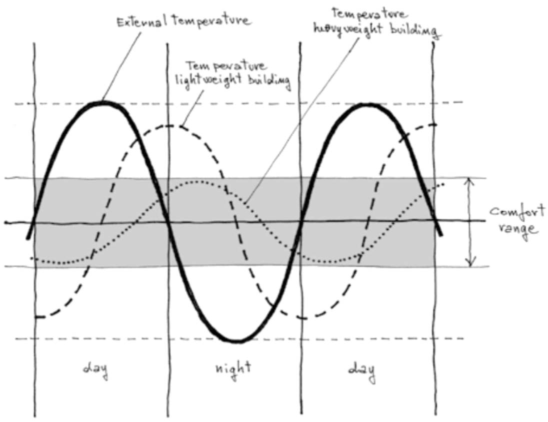

Fig. 8.21 - Effect of thermal mass on internal temperatures @UN-HABITAT

- **Building shape**

The building shape plays a role in the heat exchange between indoor and outdoor. The larger the external surface the greater are the exchanges. To preserve an internal climate different from the external conditions, one important parameter to study is the ratio surface to volume. The more compact shapes, such as dome, cone, cylinder, or cube, have a low ratio which characterizes minimised exchanges with the exterior. However, minimizing the external surfaces can also limit access to wind and daylight and the different strategies should be weighed depending on the local conditions and priorities.

The thickness of the envelope is of utmost importance for the use of thermal mass strategies. The thicker the walls, the more the indoor temperature will be delayed. Once again, thicker walls can limit the access to natural ventilation and daylight. The strategies of thermal mass are well adapted to dry climates, which have lower need for ventilation during the day.

The cylindrical Mandinka house is an example of compact shape. As well as helping with structural integrity, the conical shape of the roof limits the heat gains from the exterior.

- **Building materials**

The thermal mass is induced mostly by the choice of materials to compose the building envelope. It is characterized by two physical factors: the dephasing measured by the diffusivity, and the heat absorption measured by the effusivity.

The diffusivity of a material characterizes the propagation speed of heat inside a material relative to the heat stored inside of the material. As presented in fig. 8.20, materials are chosen to have a dephasing adapted to the period of occupancy of the building in order to delay the heatwave during outside school hours. The lower the diffusivity, the larger is the delay between outdoor and indoor temperatures. The delay can also be increased by thickening the walls.

The effusivity of a material measures its capacity to absorb or return heat. The higher the effusivity, the faster the material can store heat without its surface temperature rising. This is the characteristic most correlated with the material density. The heavier the material, the faster it stores heat while staying cool to the touch.

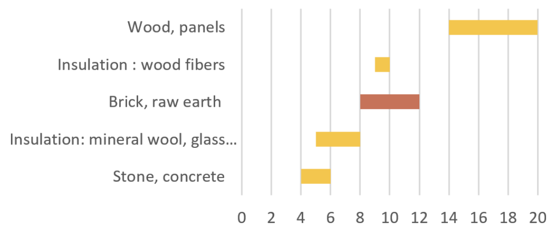

Fig. 8.22 - Thermal dephasing in hours induced by 20 cm of material @TRIBU

The materials with high thermal mass, such as stone, concrete or raw earth are especially useful on the inside of the walls, where they can absorb the heat and return it when the building is no longer occupied. On the outside however, insulating materials are a clever option to avoid absorbing external heat and transmitting it inside of the building. The thermal mass is most useful in climates with significant temperature difference between nigh and day. Where the temperatures do not drop by much during the night, as in Baghere, the thermal mass should only be used in buildings unoccupied during the night. Indeed, if used in houses, it could overheat the building during the night when the users are sleeping. [2]

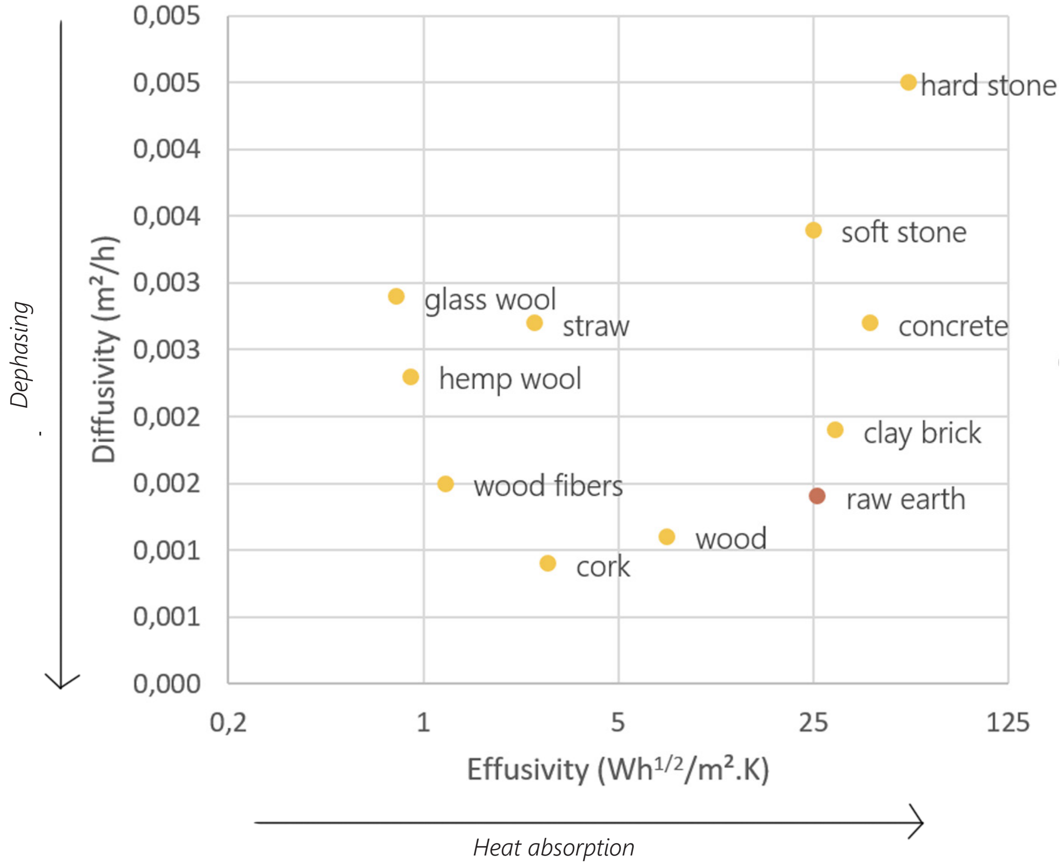

Fig. 8.23 - Thermal capacity of construction materials @TRIBU

Thermal mass characteristic has been used a lot in vernacular architecture, especially in hot-arid climates. Constructions with thick earth wall, built directly on the soil and benefitting from its thermal mass, are especially widespread in Northern Africa and desertic climates in general. The traditional Mandinka house, with its adobe or stone walls, and its insulating thatch roof is also a prime example of this passive solution. [6]

Fig. 8.24 - Traditional Mandinka houses @Balouo Salo

- **Roof**

The domed roof, although being the most compact, also receives most direct daylight all around the day. It should be made of materials with a high thermal mass and preferably in climates where the temperature drops during the night to evacuate easily all the heat stored during the day. In climates with low-variating high temperatures, an insulated roof is preferable. Indeed, the roof is usually the interface receiving the most solar gains. A thatch roof or a reflective metallic roofing combined wth ventilation is better suited in this case.

- **Directing the solar radiation**

The solar radiation entering the rooms should as much as possible be redirected towards the elements with high thermal mass which can absorb it and return it when the temperatures drop. The floor normally receives the direct radiation through the openings. If the floor is an element of thermal mass, it can be coated with dark rough materials to enhance its absorbing power. If the walls are the elements bearing the most thermal mass, the floor can be coated in light colours and reflective surface to reflect the radiation towards the walls.

2.c. Solar design

The sun is the source of both heat gains and daylight. The design of the buildings should therefore be studied to limit the solar gains while still allowing good daylight into the spaces.

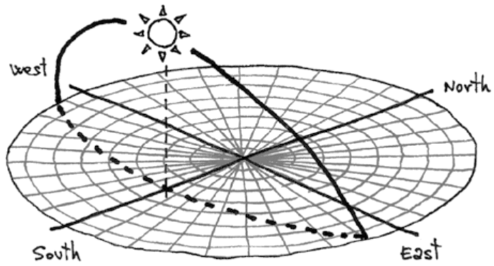

Fig. 8.25 - Solar path diagram @UN-HABITAT

- **Masterplan**

While planning the external areas, a lot can be done to limit direct solar radiation onto the surfaces of the building and through its opening. Green borders of vegetation can shade the area and constitute islands of freshness. Water bodies also enable to reduce heat around the buildings. A parameter to consider is the albedo. It characterizes the quantity of solar radiation a surface reflects. The lighter, smoother and dryer surfaces have an albedo close to 1, meaning they reflect most of the radiation. Reflective surfaces around the building can create problems of glare and important solar gains.

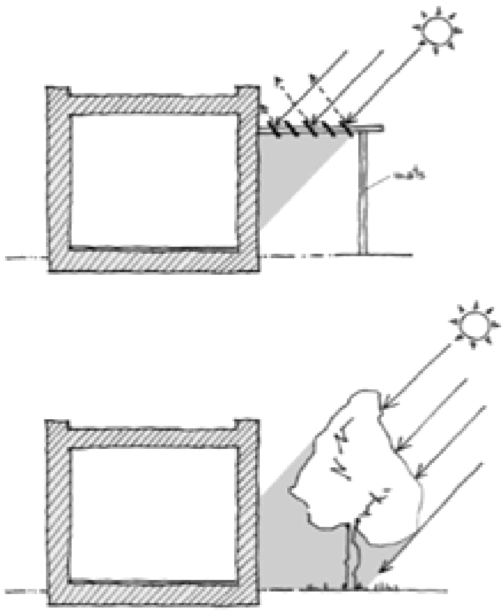

Fig. 8.26 - External shading solutions @UN-HABITAT

- **Bulding shape**

The shape of the building can have significant impact on the solar gains. The size of the openings can be characterized by the transparency of the building which is the ratio of openings to the external surfaces. The solarisation introduces the idea of exposition, considering the ratio of openings to external surfaces by orientation. Indeed, the façades on which the openings are placed can be strategic. As seen in the climate analysis, near the tropics the sun is rather high during the day, limiting the direct exposition of the South and North façade. The East and West façades are the one receiving most direct sunlight. A good strategy can be to orientate the buildings to have the most important façades facing North and South. The other façades should be shaded accordingly, for example with overhead shade or verandas serving as a buffer space. If this orientation conflicts with prevailing winds, the better compromise should be found depending on local conditions and priorities.

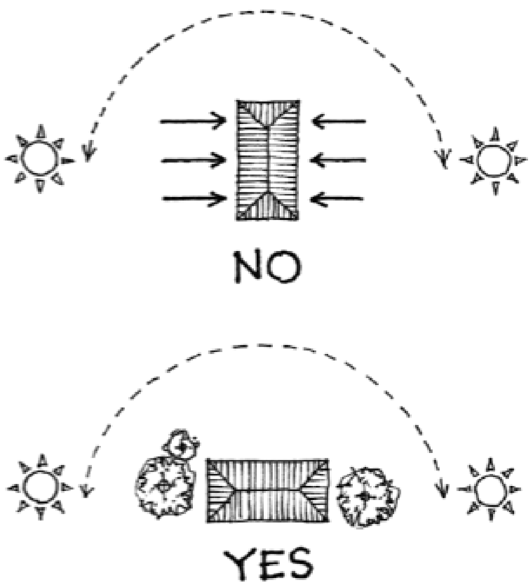

Fig. 8.27 - Orientation of the buildings according to the sun path @UN-HABITAT

In the floorplans, the position of the rooms can be chosen strategically to give more daylight to the spaces that require it and leaving the East and West façades to the storage rooms or other technical spaces. Roof overhangs mostly help shade North and South façades and should be no less than 0.6m and preferably as wide as 1

- **Walls**

The walls in hot-humid climates should be when possible reflective and light coloured to prevent heat gains. They should also be shaded either with external solutions such as roof overhangs, vegetation and canopies or with a double skin as described in the ventilated wall solution.

- **Openings**

The openings should be dimensioned according to the need for daylight while always taking into account the need for natural ventilation. As a general rule for tropical climates, they should not take up more than 20% of the wall area. To further refine the solar radiation intake, several passive shading solutions can be implemented.

- Overhead shading

Overhead shading is especially useful to block the sunlight when the sun is high in the sky, which means it can be efficient mostly on North and South façades. It can be made of a single opaque element or of multiple blades to filter the light without completely blocking it out. Towards the West and East this solution becomes inefficient as the sun comes down.

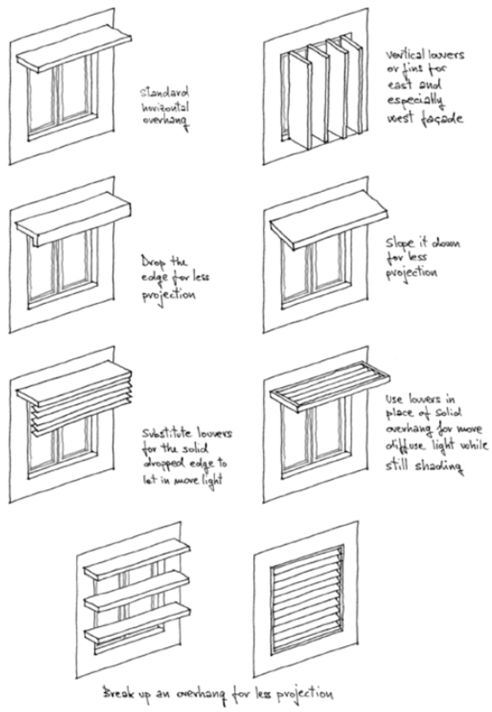

Fig. 8.28 - Different overhead and louver solutions @UN-HABITAT

- Louvres

Louvres offer a good control of the sunlight. The angle of the blades can be studied and adapted thoughout the day, to be optimal. The space between blades is another adjustable parameter that can help obtaining the right amount of daylight. To avoid solar gains, they should either be made of an insulating material (wood for example) or be reflective. Reflective blades, if tilted a certain way can also become a way to receive more sunlight

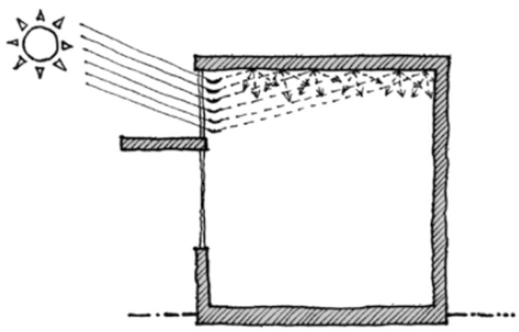

Fig. 8.29 - Reflective blades @UN-HABITAT

Different types of louvres have been used in vernacular and modern architecture alike. Some louvers are fixed, other can be rolled up or opened up like shutters. They can have vertical or horizontal blades and different dimensions. F. Kere uses folding louvers that can become overhead shading when folded. This shading solutions can become defining parts of the architecture. Another example is the Dwabor kindergarten in Ghana designed by ARUP which includes rotating colourful bamboo louvres..

Fig. 8.30 - Colourful bamboo louvres at the Dwabor Kindergarten @ARUP

- Perforated wall

In bricks walls, an easy solution to let some light in is to design perforated wall. The wall should be thin enough on this area to let enough light through. This technique can allow the creation of different shapes and patterns. This solution does not let a lot of daylight through, and it should serve on façades that receive too much direct light.

This solution has been first used in clay brick masonry, but some modern architectures have introduced it in raw earth walls. One example is Fass School in Senegal designed by Toshiko Mori, which has used perforated mud bricks walls.

Fig. 8.31 - Perforated walls in Fass school by Toshiko Mori @Iwan Baan

- Mashrabiya

The mashrabiya is a vernacular architectural element characteristic of the Islamic world. It is a type of window protected by a carved wood lattice. Its purpose is to catch wind for passive cooling while preserving intimacy inside. Jars filled with water could also be placed in the lattice to channel evaporative cooling and increase humidity indoors. The mashrabiya also serves a decorative purpose introducing various patterns and can also be lined with stained glass.

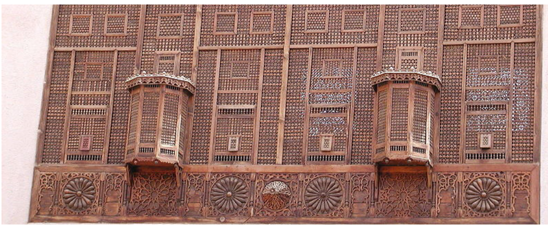

Fig. 8.32 - Traditional mashrabiya in Cairo, Egypt @Gerard Ducher

The mashrabiya is now being reintroduced in bioclimatic buildings with some modern variations. In fact, the mashrabiya is sometimes made from different materials, such as burnt bricks.

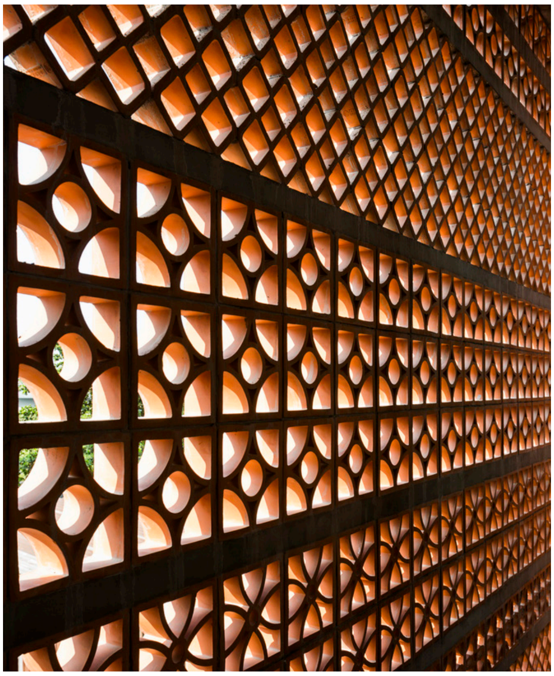

Fig. 8.33 - Modern interpretation of the mashrabiya by Sanuki Daisuke Architects @Hiroyuki Oki

- Light shelf

If the space needs more daylight, but the openings are limited to avoid heat gain for example or preserve the structural integrity of the buildings, a solution can be a light shelf. This opaque shelf place inside the opening and preferably light-coloured or reflective can redirect more sunlight inside of the spaces. According to its position and dimensions it can let in more or less daylight and direct it towards the ceiling, preventing incomfortable direct light for the users.

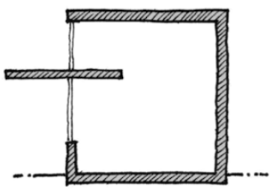

Fig. 8.34 - Light shelf @UN-HABITAT

3. HYGROTHERMAL COMFORT STRATEGIES

As we saw from the climate analysis, the challenges for hygrothermal comfort will be to decrease the indoor temperatures most of the year, while controlling the humidity levels. In our project, this objective is reached out using the three main strategies declined above: natural ventilation, hygrothermal capacities of building materials and solar protection. Each mechanism is exploited through multiple design choices and declined in different techniques.

3.a. Natural ventilation

- **Masterplan**

The orientation of the building is the first step. It was greatly influenced by the street network, as explained in the architectural design in part V. However, this orientation also exposes two main façades to the prevailing wind. The South-West façade receives the wind most of the year and the North-East façade faces the wind in the winter. With wind coming at a 90° angle to the walls, the cross ventilation can be most effective. The built project made of relatively small modules staggered with each other is inspired by vernacular architecture and allows every building direct access to the wind.

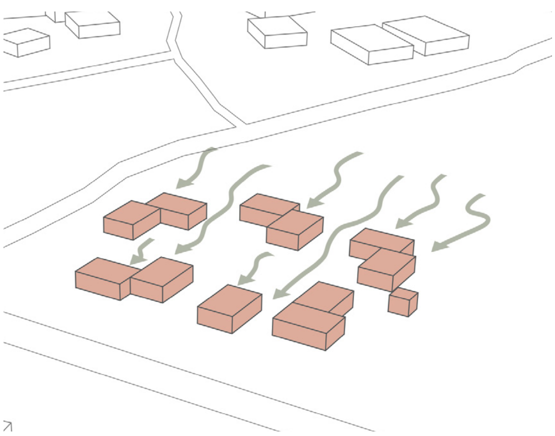

Fig. 8.35 - Access to the wind in the project

- **Cross ventilation**

The openings have been generously dimensioned. A rapid calculation based on the UNI 10339 recommended minimum amount of airflow by person allows us to find the minimum net free area on each wall of the classrooms.

Number of people	30	people
Flow rate per person	0,5	l/s/person
Required flow rate	15	l/s
Q Flow rate	0,015	m^3/s
k coefficient of effectiveness	0,6	
v outdoor wind speed	1,8	m/s
Net free area of inlet	0,014	m^2

Tab. 8.1 - Calculation of minimum net free area of inlet for UNI 10339 compliance

The minimum opening dimensions for a certain airflow was calculated using the formula:

$$Q = k\ A\ v$$

Where:
Q is the air flow rate
k is the coefficient of effectiveness depending on the orientation of the openings in relation to the wind, v is the outdoor wind velocity
A is the net area of inlets.

The net free area of the window was calculated considering the blades inclined with a 30° angle.

Total area of the window	0,57	m^2
Area blocked by a 30° blade	0,02	m^2
Number of blades	14	
Net free area of the window	0,23	m^2
Net free area of the wall	1,39	m^2

Tab. 8.2 - Calculation of the minimum net free area of a classroom wall

We can see that the opening of one window is already sufficient for the simply hygienic ventilation of a classroom containing 30 students. The total free area of the least opened wall contains six windows which represent a total opening of 1,39 m². In our case, the ventilation is indeed not only hygienic, but it also serves the purposes of dehumidifying and cooling down the indoor air. Although hard to simply evaluate, natural ventilation can maintain an indoor temperature inferior by as much as 5 degrees to outdoor conditions in hot climates. [3]

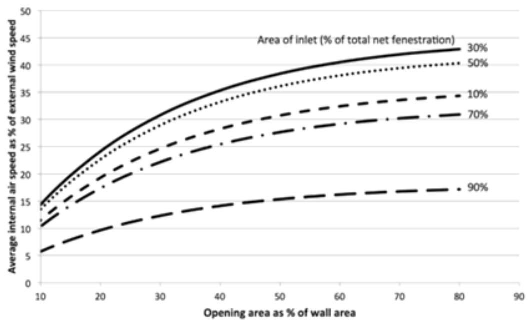

Fig. 8.36 - Average indoor speed according to the % of openings to wall surface @UN-HABITAT

From the ratio of openings to the whole surface of the wall, we can deduce the indoor wind speed. In this project the openings represent around 15% of the wall total surface. That means that the indoor air speed will be around 20% of the outdoor speed. The indoor air flow will be around 0.36 m/s which is hardly noticeable by users and shouldn't create discomfort.

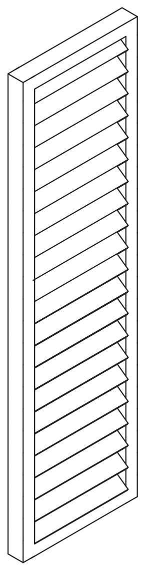

Fig. 8.37 - Window louvre of the project

The classrooms have long windows, 160 cm-tall for 60 cm-wide. The height of these windows favour ventilation, allowing the stack effect to complement the wind in conducting the airflow. On the other side of the classroom, the accordion doors that open towards the openair classroom are 2,4 m tall and are opened all the way. The openings on the two long sides of the building introduce cross ventilation in the spaces. The ventilation crosses 6 m, which is a little over twice the ceiling height and is well below the maximum recommended depth of 5 times the ceiling height. Both windows and doors are equipped with wooden louvres, necessary for visual comfort that slightly reduce the net area of the openings. The vaulted ceilings also helps creating air movement and favours natural ventilation.

- **Raised floor**

The raised floor, supported by reused tyres also create a ventilated cavity to help reduce heat gains as well as moisture infiltration. The soil has a great thermal inertia and can therefore store heat and transfer it to the building through the floor. The airflow between soil and floor helps reducing the heat transfer. Moreover, the humidity can rise from the ground into the wooden and raw earth structures that are sensible to moisture. The ventilated cavity serves this dual purpose of keeping the floor away from heat and moisture.

- **Double roof**

The double roof is used in the project to reduce solar heat gains. The outer layer is a corrugated iron sheet, which reflects part of the radiation while also protecting the building from the rain. Underneath the roof, the wind can circulate above the ceiling, evacuating part of the heat trapped.

The massive ceiling made of raw earth can absorb heat and release it when temperatures drop. The diffusivity of the earth is low; therefore, the heat takes hours to get across the ceiling, leaving the indoor environment cool. The use of clay-straw lightweight loam channels the insulating power of the straw to keep the heat outside in the ventilated space between roof and ceiling.

To put in a nutshell, the double roof system includes three shields against solar heat gains: the reflective surface, the interface ventilation and the thermal mass and insulation of the ceiling.

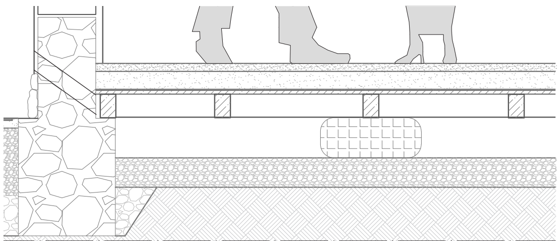

Fig. 8.38 - Detail of the raised floor

1. Orientation of the facades
2. Double roof
3. Natural ventilation
4. Hygrothermal regulation by raw earth
5. Vegetation and external shading

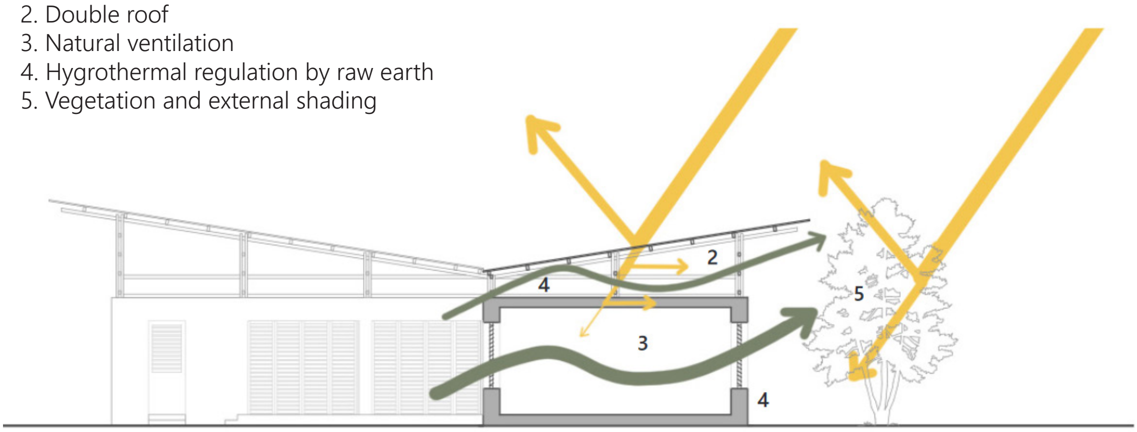

Fig. 8.39 - Thermal comfort strategies diagram

3.b. Hygrothermal capacities of materials

- **Raw earth hygrothermal charecteristics**

Raw earth behaves as a thermal and hygrometric regulator. It means that it slows and attenuates heat transmission, having an important thermal mass. It also stabilizes indoor relative humidity better than other building materials. Both characteristics allow raw earth buildings to preserve a breathable atmosphere indoor with softer variation than outdoor conditions. This physical behaviour is explained by different mechanisms at the macro and micro scale :

- A high thermal inertia and heat storage due to an important density of the material

- A change of state of the water contained inside the pores of the material, which leads to the evaporation of hot temperatures therefore absorbing heat. In cooler periods the water will condense releasing heat.

- A transfer of water vapour through the wall in the open network nanopores, facilitating absorption or release of moisture depending on the ambient humidity

Regarding thermal capacities, as already mentioned, raw earth has a high thermal mass. Heat take time getting across the thickness of the walls (low diffusivity), and the exposed surfaces have a great heat absorbent capacity (high effusivity). The thermal mass is also described by the volumetric heat capacity C (J/m^3.K). It means that the 30 cm raw earth wall in the project should create a dephasing of 12 hours inside the building, allowing the afternoon heat to be released in the early morning.

The capacity of exchanging moisture through the external and internal envelope of the buildings is characterized by the vapour diffusion, or the water vapour permeability. The resistance factor to vapour diffusion μ is the ratio between the water vapour permeability of air and of the material. In raw earth material, it decreases when the relative humidity increases and varies between 5 and 13. It is fairly low and can be compared to the values found for glass wool. As a comparison, burnt brick have a vapour resistivity between 45 and 70, and concrete blocks between 15 and 150. This explains why an appropriate plaster letting through vapour should be put on raw earth elements. Raw earth has a high capacity of exchanging water vapour with the environment, regulating humidity levels.

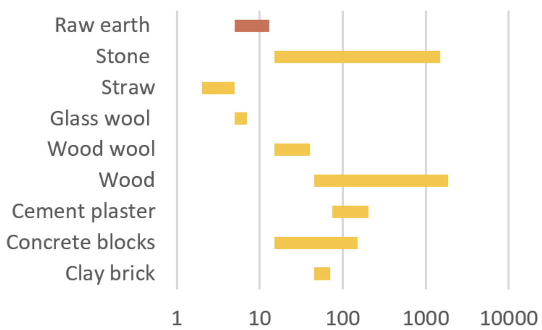

Fig. 8.40 - Vapour diffusion resistance range for different materials [G N s/(kg m)] @Engineering Toolbox

- **Fibres**

The addition of vegetal fibres into the earth changes its thermal behaviour. Mechanically, their role will be developed more in the research on bio-bricks in part IX. On a thermal point of view, adding vegetal fibres in the earth decreases its density, therefore it also decreases its thermal mass capacities.

However, by aerating the earth, it makes the material more insulating. Straw for example has good insulating properties with a thermal conductivity around 0,15 W/(m.K). [8] This characteristic has been used in the project by using clay-straw lightweight loam as a filling material. The thermal conductivity of this type of material is ¼ of compressed earth's one. Used in the ceiling and floor, it diminishes effectively heat gains through these sides.

Fig. 8.41 - Wood fibers used in brick experiments

- **Insulation**

Insulation is an important strategy for the climate of Baghere, where the temperatures are high and don't decrease much during the night. To characterize the insulation of the envelope, the U-value is calculated for every building element. The insulating capacity is described by the thermal conductivity λ (W/m.K) also named k-value.

Material	Thermal conductivity [W/(m·K)]	Source
Lightweight straw loam	0.21	Building with earth [8]
Compressed earth blocks	0.85	Sustainability [7]
Lime plaster	0.82	IES
Clay plaster	1.1	Applied clay science [9]
Samba wood boards	0.15	IES

Tab. 8.3 - Thermal conductivity of materials

The thermal transmittance, also known as U-value, is then calculated for the element. First, the insulance of each layer is found by multiplying the conductivity λ of the material with the thickness of the layer. All the insulances are summed, and the inverse of that sum gives the U-value of the element. The lower the U-value, the better is the element isolation.

Material	k-value [W/(m·K)]	Thickness (cm)	Insulance [K·m²/W]
Lime plaster	0,819	2	0,02
Compressed earth blocks	0,85	30	0,35
Clay plaster	1.07	4	0,04
Total insulance			0,41
U-value (W/(m2·K))			2,41

Tab. 8.4 - Calculation of the U-value of the walls (W01)

Material	k-value [W/(m·K)]	Thickness (cm)	Insulance [K·m²/W]
Lime plaster	0,819	2	0,024
Lightweight straw loam	0,21	8	0,38
Compressed earth blocks	0,85	9	0,11
Total insulance			0,51
U-value (W/(m2·K))			1,96

Tab. 8.5 - Calculation of the U-value of the Jack arches ceiling (C01)

Material	k-value [W/(m·K)]	Thickness (cm)	Insulance [K·m²/W]
Lime plaster	0,819	2	0,024
Lightweight straw loam	0,21	10	0,48
Wood boards	0,85	9	0,13
Clay plaster	1,07	4	0.037
Total insulance			0,67
U-value (W/(m2·K))			1,49

Tab. 8.6 - Calculation of the U-value of the coffered ceilings (C02)

Material	k-value [W/(m·K)]	Thickness (cm)	Insulance [K·m²/W]
Lime plaster	0,819	4	0,049
Lightweight straw loam	0,21	10	0,48
Wood boards	0,15	4	0,27
Total insulance			0,79
U-value (W/(m2·K))			1,26

Tab. 8.7 - Calculation of the U-value of the indoor floor (F01)

The Senegalese standards for insulation does not impose minimum values but guidelines. It was not unfortunately inaccessible at the time of the research. The insulation of the roof is the utmost priority as it receives the most solar gains. [10] The maximum U-values according to the Italian normative are listed in Tab. 8.8.

Building element	Maximum U-value for B-zone (Sicily)
Flat roof	0.65
Inclinated roof	0.34
Floor	0.48
Wall	0.45

Tab. 8.8 - Maximum U-values for building elements @D.M. 26 june 2015 Italy

We can therefore see that the faces of the buildings are not insulated as much as European standards require. We must consider that this normative is in use in countries where the winter temperatures drop significantly, requiring a consequent insulation.

Even if the U-values of the project's elements are rather high, this is explained by the fact that the design priorities where the ventilation and a limited use of materials. Indeed, the building's openings have no glazing and therefore they would be considered as unacceptable thermal bridges in European countries. Actually, the low insulation of the building puts even more emphasis on the role of the passive strategies described in this chapter. The building is not a closed box with limited contact with its environment but instead it is opened and connected to the natural flows around it: airflow, water vapour, and solar radiation. The focus is more on the control of these flows in and out of the buildings rather than on barriers put up against them.

3.c. Solar protection

- **Shading**

Shading is one of the most important strategies in the climate of the South of Senegal. Indeed, having shading area protected from the direct ray of the sun is crucial. Thus, the roof overhangs were generously dimensioned to expand 1,5 m around the walls of each building. As well as sheltering the walls from the rain, it also shades the surroundings and the walls themselves diminishing the solar heat gains through the building envelope.

Another key feature of our project are the canopies built in wood and covered with local fabrics. They also shade the outdoor areas in proximity of the buildings as well as the walls when the sun gets too low for the roof to play this role. The extensive placement of canopies along the western façades is no coincidence for these walls, as they are the most exposed to direct sunlight.

- **Vegetation**

The use of vegetation is also strategic. Placed in the centre and along the buildings they cool down their surroundings by evapotranspiration and by the shading they provide. The vegetable gardens placed directly along the buildings also have these beneficial traits.

Fig. 8.42 - VIew of the canopies and vegetation

4. VISUAL COMFORT STRATEGIES

4.a. Daylight strategies

- **Openings position and size**

As seen in the tropical bioclimatic strategic, the main openings should be located on the North and South façades which receives daylight during the day and can be easily shaded. The openings along these façades were thought out as long openings with louvres.

The East façade receives more direct sunlight in the morning. No large openings were placed along these walls, and some classrooms which require more sunlight have windows with louvres.

The West façade is the most critical receiving direct sunlight in the afternoon when the sun is low enough to render useless any overhead shading. That is why the openings on this side were designed as perforations in the brick wall pattern. They will significantly reduce the amount of daylight received.

To quantify this strategies, different parameters can be used. Fisrt, the transparency is the ratio of openings to wall surface. Then, the solarization is the transparency for each orientation.

1. Shading by pergolas and vegetation
2. Roof overhang
3. Small openings on strategic facades
4. Adjustable louvers

Exposition	Solarization
South-West	0,158
North-East	0,124
North-West	0,192
South-East	0,165
Total	0,161

Tab. 8.9 - Ratio opening to wall surface of the project

In the Tab.8.9 , we can see that the two most concerning façades, the South-West facing walls and the North-East, were designed with less openings. We also notice that on every orientation, the openings do not exceed 20% of the walls, advised limit for tropical climates. [1]

- **Pergolas, overhangs, and vegetation**

Different solutions have been adopted around the buildings. As mentioned for the thermal comfort, the canopies and roof overhangs offer shading and create pleasant outdoor spaces, as well as reducing the light entering the buildings. The trees placed in the project also offer fresh oasis and shading. Indeed, vegetation can stop 60 to 90% of solar radiation. [11]

- **Louvres**

The louvres are put up on every window to allow control of the daylight. They were thought to have 10 cm openings to let people view outside comfortably. The louvres let in the air for ventilation while still blocking part of the sunlight. The angle and adjustability of the louvres were studied in the daylight study developed in the next paragraph.

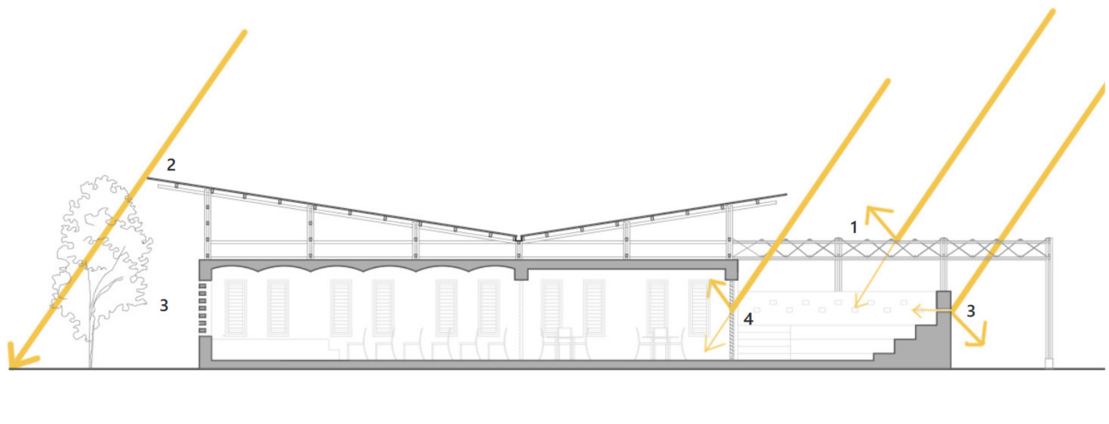

Fig. 8.43 - Visual comfort strategies diagram

Surface type	Albedo
Sand	0.75
Soil, clay	0.14
Dirt roads	0.04
Forest, plants	0.26
Dry grass	0.2
Field with soil and dry grass	0.65
Field with scattered trees	0.62

Tab. 8.10 - Albedo by type of surface @UN-HABITAT

- **Albedo**

As mentioned earlier, the albedo is the measure of the reflectivity of the surfaces. Having reflective surface around the buildings can lead to more daylight inside the rooms. The surface of the soil is that of a field with soil and dry grass. Therefore, it reflects around 65% of the light. The clay soil created for the outdoor spaces should reflect a little less radiation, with an albedo around 0.14. These surfaces have been taken into account in the daylight simulations.

4.b. Daylight analysis

One of the objectives was to obtain spaces illuminated naturally most of the time. One challenge was to avoid having spaces too bright which wouldn't be appropriate for teaching and studying. A study of the daylight was conducted with a focus on different parameters: the daylight factor and the illuminance. The first step is the definition of these parameters and limit values to consider.

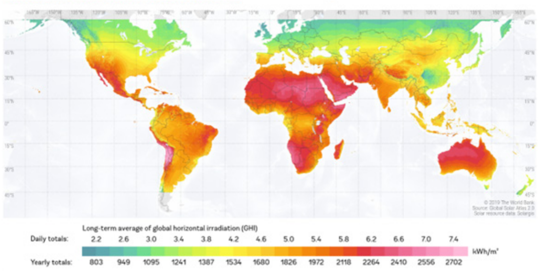

Fig. 8.44 - Global Horizontal Irradiation @World Bank Group

- **Daylight factor**

The daylight factor is an architectural term that describes the amount of natural light within a room or a structure. It is given as a ratio of the light level inside the structure to the light level outside the structure (indoor light/outside light). The measure for outside light is considered for an overcast sky. The UNI 10840 recommends for spaces in Italy a daylight factor superior or equal to 2%. Considering the ratio between the outside average irradiation in Italy and in Senegal, we can consider that the daylight factor in Senegal should be superior or equal to 1.45%. If the daylight factor becomes too important, people can face glaring problems, and it should therefore be kept under 6%.

Daylight factor in Italy (UNI 10840)	≥ 2%
Daylight factor considered in Senegal	≥ 1.45%

Tab. 8.11 - Minimum daylight factor

- **Illuminance**

The illuminance is the amount of luminous flux per unit area. It is measured in lux and is used to qualify the light on working surfaces, in our case the surface of a table. The Décret n° 2006-1252 du 15 novembre 2006 Senegal defined a recommended illuminance for different type of working spaces in Senegal, including nurseries.

The Senegalese normative do not specify any recommendation for schools, and we therefore considered the European Norm EN 12464 as a reference. This norm defines the minimum recommended illuminance depending on the function of the spaces. The values considered are listed in the Tab.8.12. These minimums are aimed at guaranteeing:

- psycho-physiological aspects such as visual comfort and well-being,
- requirements for visual tasks,
- visual ergonomics,
- safety,
- economy of energy consumption

In the daylight analysis, along with these minimums, we considered a maximum when the illuminance was over 500 lux more than the minimum to avoid problems of glare.

EN 12464	Minimium illuminance recommended
Classroom for primary school	300 lux
Gathering space-common space	200 lux
Teacher's room	300 lux
Cafeteria	200 lux
Décret n° 2006-1252 du 15 novembre 2006 Senegal	Minimum illuminance recommended
Nursery	500 lux

Tab. 8.12 - Minimum illuminance

- **Simulations**

The daylight study aims at understanding the impact of the different daylight strategies described above on the light inside the spaces at different periods of the year and hours of the day. It should allow the definition of the angle of the louvers and help determine whether adjustable louvers are necessary.

Based on climate analysis, the sky cover in the simulation was defined for different periods of the year. The most luminous month seems to be April, while the least light seems to be during the month of August. The simulations conducted on the software Dialux were therefore executed on those two extreme months. The light was also studied at different hours on the 15th of April, and at the same hour during different months.

We must keep in mind that the position of the sun varies depending on the season and the hour. The particularity of this place is that the sun can come from every direction: East in the morning, West in the evening, but also North during the summer and South during the winter. Therefore, the solutions adopted to filter the light can benefit greatly from being dynamic.

- Simple openings with no solar protection

The first analysis was conducted with simple openings and no shading to understand the source and the direction of the light and also the potential glar in spaces. The illuminance and daylight factor of each analysed space are found in Tab. 8.13. The values highlighted in blue are under the requirements and the ones in red are at least 500 lux above them.

As expected, many spaces receive too much light in April which is the most luminous month. However, some spaces such as the laboratory are not receiving enough daylight. This prompted us to rethink our openings for certain spaces. For instance, we decided to add more windows to the laboratory on the East façade.

- Simple openings with shading canopies

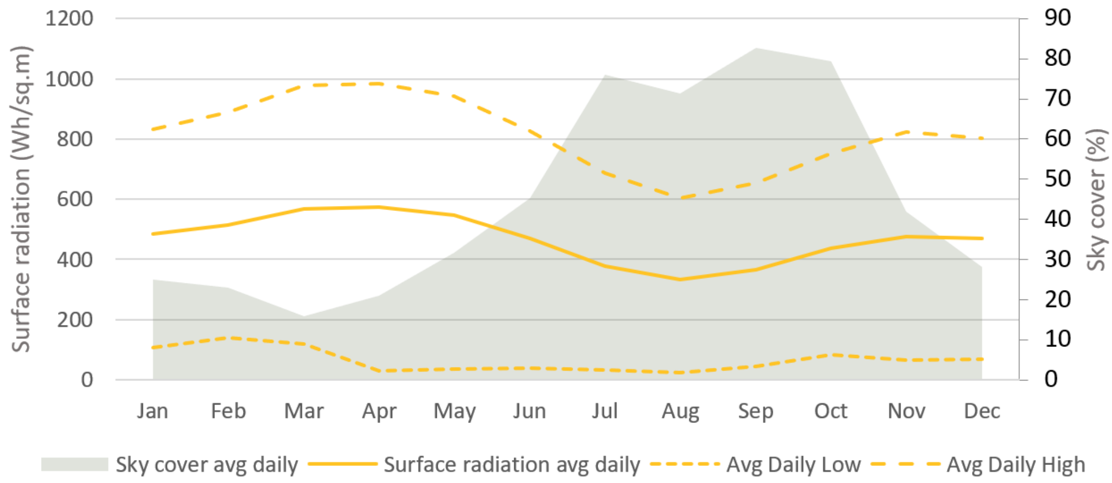

Fig. 8.45 - Solar radiation in Kolda, Senegal @NOAA

	Illuminance (lux)				
	Classroom 1.1	Classroom 1.2	Cafeteria	Laboratory	Teacher's room
Most (Apr 12h)	388	320	1586	283	511
Least (Aug 8h)	268	257	346	130	282
April 8h	3750	264	5819	139	2546
April 10h	1377	399	1881	181	1417
April 15h	300	2406	1018	1831	2690
June 12h	658	1345	2032	965	1817
August 12h	405	389	523	197	366
October 12h	452	434	583	219	408
December 12h	449	403	419	208	294
February 12h	384	401	473	202	319
	Daylight factor (%)				
	1,87	1,87	2,63	0,98	1,78

Tab. 8.13 - Simulation results with no shading solution

	Illuminance (lux)				
	Classroom 1.1	Classroom 1.2	Cafeteria	Laboratory	Teacher's room
Most (Apr 12h)	314	430	1043	328	510
Least (Aug 8h)	268	257	346	195	282
April 8h	3690	262	5743	287	2543
April 10h	1313	310	1783	282	1416
April 15h	224	2338	655	1472	2686
June 12h	562	908	1518	888	1815
August 12h	405	389	523	300	366
October 12h	345	324	502	328	365
December 12h	300	305	350	293	293
February 12h	291	313	396	283	318
	Daylight factor (%)				
	1,4	1,36	2,2	1,42	1,78

Tab. 8.14 - Simulation results with shading canopies

The second simulation was made with the addition of the canopies made of wooden pergolas and cotton fabric shading some outdoor spaces. We should also mention the addition of the windows of the laboratory on the East side. The results are listed in Tab. 8.14.

Adding the pergolas have different effects on the rooms that vary regarding their location. It had little impact on the lighting of the cafeteria. Even though the classrooms already have good daylight in different simulations, some values are way above the limit fixed and closer daylight control is needed. We notice that as predicted, the problematics are mainly in the morning or afternoon where the sun becomes lower.

- Canopies and openable louvers with fixed blades

	Illuminance (lux)				
	Classroom 1.1	Classroom 1.2	Cafeteria	Laboratory	Teacher's room
Most (Apr 12h)	314	430	183	328	266
Least (Aug 8h)	268	257	346	195	282
April 8h	326	262	509	287	309
April 10h	289	310	259	282	264
April 15h	224	579	299	493	637
June 12h	313	219	245	224	402
August 12h	405	389	151	300	366
October 12h	345	324	135	328	365
December 12h	300	305	350	293	293

Tab. 8.15 - Simulation results with openable louvers with fixed blades

	Illuminance (lux)				
	Classroom 1.1	Classroom 1.2	Cafeteria	Laboratory	Teacher's room
Most (Apr 12h)	314	430	201	328	317
Least (Aug 8h)	268	257	346	195	282
April 8h	326	262	509	287	309
April 10h	330	310	214	282	364
April 15h	224	579	299	493	637
June 12h	398	471	237	365	416
August 12h	405	389	168	300	366
October 12h	345	324	172	328	365
December 12h	300	305	350	293	293

Tab. 8.16 - Simulation results with semi-openable louvers with fixed blades

	Illuminamento (lux)				
	Classroom 1.1	Classroom 1.2	Cafeteria	Laboratory	Teacher's room
Most (Apr 12h)	314	430	345	328	303
Least (Aug 8h)	268	257	346	195	282
April 8h	326	262	345	287	309
April 10h	330	310	210	282	315
April 15h	224	444	299	383	493
June 12h	339	379	244	305	314
August 12h	405	389	216	300	366
October 12h	345	324	237	328	365
December 12h	300	305	350	293	293

Tab. 8.17 - Simulation results with openable louvers with adjustable blades

For good results at most hours of the day, the setting used was 30° blades on the façade receiving direct sunlight. Depending on the day and hour, the protected openings would vary. On the other facades, the louvers were left completely open.

We can still see a few hours in which this setting is not optimal. Sometimes, the 30° louvers block out too much light, but still need to be closed or direct sunlight penetrates the buildings and becomes blinding. In other cases, the 30° louvers do not block out enough light. The best option would then be to have adjustable louvers, which can be more expensive but allow a better control of the light throughout the days and the year. One option is to have louvers with fixed blades that can be partially opened. The other option is to use adjustable blades. Both solutions were tested and compared.

- Canopies and semi-openable louvers with fixed blades

This system has allowed to raise the illuminance in some situations where the space was too dark. The downside is that the partial opening of the more exposed windows often creates spots of direct light, that could potentially degrade the user experience. The uniformity of the lighting in the rooms is far from ideal in some cases.

- Canopies and openable louvers with adjustable blades

Finally, we tried adapting the angle of the louvers for each hour of the day and found some optimal results every time. The solution is not totally realistic as adjusting perfectly every hour would require much work from the professors or children, but providing the option to adjust the blades could at least help the teachers avoid blinding lights or excessive darkness.

It should be noted that this system blocks direct sunlight into the room while still allowing enough daylight. This system is the one that gives the most homogeneous lighting. It can although be more complicated to build and thus more expensive.

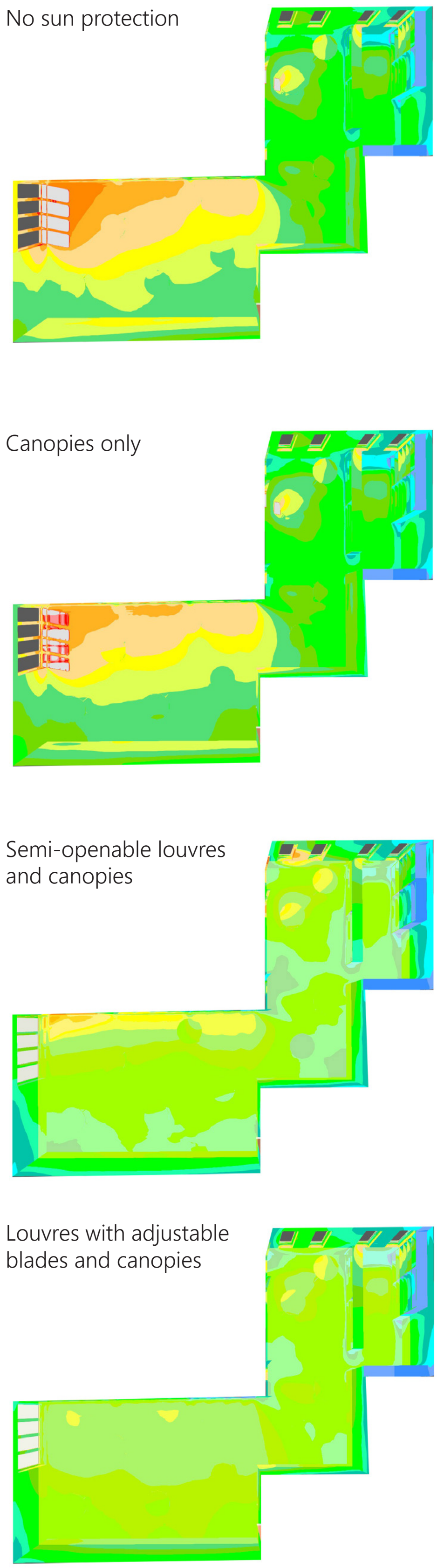

Fig. 8.46 - Simulation results of the cafeteria on April 21st at 12am with a clear sky

5. RAIN PROTECTION

5.a. Rain protection strategies

The roof overhang of 1,5 m not only shades the building's surroundings but also serves the purpose of protecting the earth ceiling and walls from the tropical rain. The compressed earth bricks can resist partial erosion on the surface in case of water projection, as studied in chapter IX, but they should be protected from direct rain exposition. The ceiling also has a lime-casein plaster coating to protect it in case of localised leakage from the roof, but it cannot resist substantial water exposition. The roof overhang is made to protect it even from diagonal rain drops.

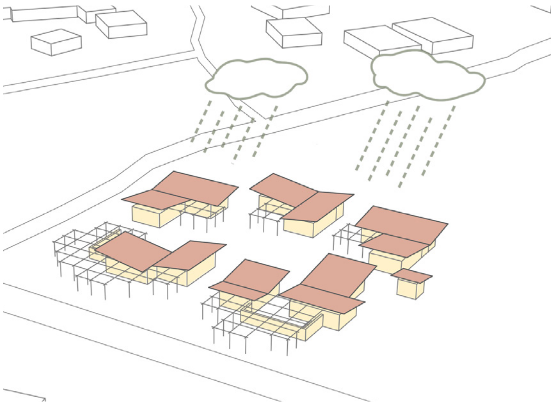

Fig. 8.47 - Protection from the rain

The external floors directly exposed to the rain are made with earth stabilized with cement to make sure they are water-resistent. This way, the pathway can be guaranteed even during the rain season.

The base course around the buildings also helps protect the walls from humidity and preserve them from the ground that can get wet and muddy in the rainy season. As mentioned in chapter VI, all foundations are surrounded with drainage pipes, buried under layers of gravels and stones.

The raised floors also serve the purpose of avoiding flooding inside of the buildings in case of important rainfall. The layer of gravel underneath the tyres should be able to drain water and avoid it reaching the wooden supports of the floors.

5.b. Drainage system

The rainwater drainage system was designed according to the UNI EN 12056 implemented in Europe due to a lack of resources on the Senegalese standards. To dimension the rainwater network, the first data is the rainfall intensity which is of 88 mm/h in the region. [12] The design flow load needs to be calculated for each roof using the following equation:

$$Q = I \times A \times C \times C_r \text{ [L/s]}$$

With: Q, the flow load of the gutter
I, the rainfall intensity
A, the area of the roof
C, the run-off coefficient, depending on the typology of the surface of the roof
C_r, the risk coefficient regarding the type of gutter and the function of the building. Having a valley gutter above a water sensitive ceiling, the risk coefficient is 2.

Exposed roof surface	220	m²
Length of the gutter	9,4	m
Run-off coefficient C	1	
Risk coefficient Cr	2	
Design flow load	10,8	L/s
Number of down-pipes	2	
Reduced design flow load	5,4	L/s

Tab. 8.18 - Calculation of the design flow load for a classrooms' building

Exposed roof surface	198	m²
Length of the gutter	6.5	m
Run-off coefficient C	1	
Risk coefficient Cr	2	
Design flow load	9.68	L/s
Number of down-pipes	2	
Reduced design flow load	4.84	L/s

Tab. 8.19 - Calculation of the design flow load for the cafeteria building

Exposed roof surface	198	m²
Length of the gutter	9,4	m
Run-off coefficient C	1	
Risk coefficient Cr	2	
Design flow load	9.68	L/s
Number of down-pipes	2	
Reduced design flow load	4.84	L/s

Tab. 8.20 - Calculation of the design flow load for the laboratory building

Exposed roof surface	109	m^2
Length of the gutter	9,4	m
Run-off coefficient C	1	
Risk coefficient Cr	2	
Design flow load	5.33	L/s

Tab. 8.21 - Calculation of the design flow load for the teacher's room building

Exposed roof surface	29	m^2
Length of the gutter	5.5	m
Run-off coefficient C	1	
Risk coefficient Cr	2	
Design flow load	1.42	L/s

Tab. 8.22 - Calculation of the design flow load for the toilets building

The higher flow load is found for the classroom's building's roof and can be divided by choosing to create two down pipes for the gutter. This allows us to choose the format of the gutter by calculating the design flow rate of the gutter. The nominal flow rate is found with the following equation:

$Q_N = 2.78 \times 10^{-5} A_E^{1.25}$ [l/s]

Where A_E is the hydraulic section of the gutter.

Then the design flow rate is calculated in Tab. 8.23 with this formula:

$Q_L = 0.9\ Q_N \times F_L$ [l/s]

Where F_L is the coefficient of capacity depending on the ratio length to width and of the inclination

Width	160	mm
Height	120	mm
Hydraulic section A_E	19200	mm^2
Nominal flow rate Q_N	6,28	L/s
Coefficient of capacity Fl	1	
Design flow rate Q_L	5,65	L/s

Tab. 8.23 - Calculation of the design flow rate of the gutter

of the gutter.

The chosen section is rectangular with dimensions of 160 mm x 120 mm, the height being limited by the design of the roof structure. The down pipes are then dimensioned using tables giving the flow rate for a given diameter and percentage filled. For these roofs, an 80 mm pipe is sufficient.

The pipes collecting the water from the different downpipes and direct it towards the water tanks, are dimensioned using Tab. 8.24. To avoid excessive excavation, the slope was limited to 1%.

	Pendenze in %							
	0,5%	1,0%	1,5%	2,0%	2,5%	3,0%	4,0%	5,0%
ø mm	Portata in l/s							
69/75	1,3	1,8	2,3	2,6	3,0	3,2	3,8	4,2
83/90	2,0	2,8	3,4	4,0	4,5	4,9	5,6	6,3
101/110	3,6	5,0	6,2	7,2	8,0	8,9	10,2	11,5
115/125	5,2	7,4	9,0	10,5	11,7	12,9	14,9	16,7
147/160	10,0	15,0	18,0	21,0	23,5	26,0	30,0	33,0
187/200	19,0	27,0	33,1	38,1	42,8	47,0	54,3	60,8
234/250	34,5	49,0	60,1	69,5	77,7	85,2	98,4	110,1
295/315	62,8	90,6	111,1	128,4	143,6	157,4	181,8	203,3

Tab. 8.24 - Dimensioning of horizontal pipes for drainage

5.c. Rainwater collection

The rainwater is collected in our project into three underground tanks to serve different purposes. As the temperatures can increase significantly, burry the tanks in the soil, enable to saves the stored water from these high temperatures. Moreover, the material of the tank can influence the heat transmission to the water because of its thermal mass. Besides, maintening a temperature lower than 30°C in the tank avoid the formation of bacteria which are formes between 35 and 46°C, and thrive in water temperatures of between 30 and 50°C.

The three water tank are located the nearest to the function they have to supply. One is found near the toilets to give access to water for hand washing and cleaning of the pit latrines. The second one is found in the centre and supplies the tap water for the cafeteria and the kitchen. For both usage, important filters should be implemented as well as regular controls should be done to ensure the water cleanliness.

The last tank is found near the gardens and serves as a water reserve for gardening during the dry season to ensure a continuous supply of local healthy food.

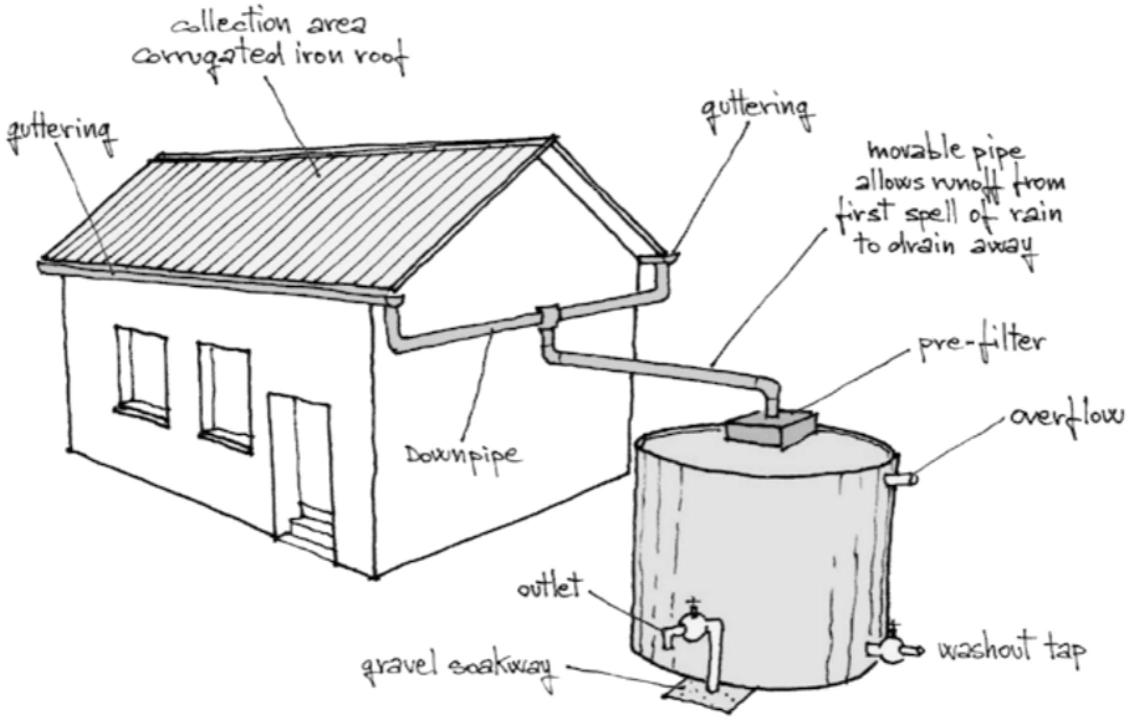

Fig. 8.48 - Rainwater collection diagram @UN-HABITAT


@Kere Architecture

IX. RESEARCH ON BIO-BRICKS

IX. RESEARCH ON BIO-BRICKS

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8. Conclusion 224

1. PRELIMINARIES

1.a. Objectives

The objective of this experimental research is to transform raw earth into a building material that responds to contemporary needs.

The technique of compressed earth bricks is being used in this study. It has been chosen over the other techniques presented in §III, as it is one of the best technique in terms of mechanical resistance and ease of implementation on site. Compressed earth bricks are traditional masonry elements made with clay, sand and silt. They can be reinforced with local fibres and held together by mud mortar. They are cast on-site with a compressive machine and dried under the sun. As we were not able to visit the site and thus bring local raw earth to test it, the earth material used in the fabrication of the bricks is from Italy.

To transform raw earth into a building material, the proportions of fibres and water are crucial and impact the mechanical performances of the material. Three types of fibres have been chosen to be tested for the bio-bricks : bamboo, straw and wood, as they are locally available and have interesting characteristics.

To evaluate their proportion different tests will be conducted. First, the Carazas test will enable to evaluate approximately the water proportion and the way of compressing using the three phases composing raw earth. Then, to evaluate the proportion of gravels added to enhance mechanical resistance, a similar test will be conducted. Finally, to evaluate the proportion of fibres, mix design tests will be carried out. To choose the best solution adapted to the school, each bricks will then have their mechanical and environmental performances evaluated.

Regarding their mechanical performances, they will be subjected to compression and erosion tests. For the environmental aspect, their Life Cycle Assessment will be evaluated in §X.

All these tests results will enable us to choose the bio-bricks that are best adapted to the construction of the school.

1.b. Granulometric composition

In order to compare our material to local earth resources in Baghere, its granulometric composition is first compared.

In Baghere, the soil is mainly ferralitic due to the salt in the valley that has oxidised the soil. Thus, it implies that its soil composition is mainly kandic minerals (over 90%), associated with iron and aluminium sesquioxide. [1]

On the other hand, the raw earth material used has the following composition found with the sedimentation method to determine grain size distribution. [2]

Apertura (mm)	% passante
2.000	100.000
0.840	99.503
0.420	98.509
0.177	96.024
0.150	92.942
0.106	90.358
0.0710	82.57
0.0509	78.44
0.0364	74.31
0.0261	70.18
0.0193	53.67
0.0144	45.41
0.0103	39.22
0.0073	37.16
0.0052	33.03
0.0037	30.96
0.0027	28.90
0.0016	24.77

Fig. 9.1 - Result of the grain size test @H. Xinyue

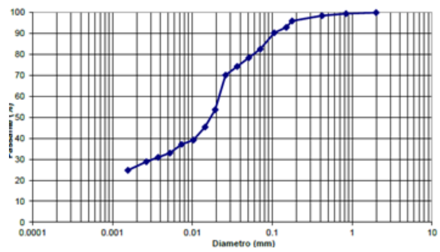

Fig. 9.2 - Granulometric curve @H. Xinyue

From the chart, we can establish that around 20% of the soil is sand and around 80% are finer particle. To establish the proportions more precisely, the particles sizes are gathered regarding the particle sizes of sands, clay and silts. Indeed, sand particles are elements larger that 0,05 mm, silt particles are between 2 µm and 50 µm and clays are smaller than 2 µm. [3]

Thus, in the soil used for the experiments, there are around 24,8 % of clay, 53,7 % of silt and 21,6 % of sand. One can state that the earth has a silty texture and is a clay-sand soil. The composition is different from the one that should be found in Baghere. Around Sedhiou, the soil contains around 52 % of clay and 23 % of silt. [20] This high clay content makes it well-adapted for construction, with interesting mechanical properties Even though the earth material used for experiments isn't the same as the one in Baghere, it is more vulnerable and so its established mechanical resistances will probably be smaller. Hence, local bricks should have a better mechanical resistance than the one studied.

2. CARAZAS TESTS

2.a. Experimental process

To have a first estimate of the water proportion and understand the impact of compression in transforming raw earth into a building material, a Carazas test is performed. As explained in §.III, this test highlights how to turn raw earth into a building materials using the three phases involved. It is accessible to all due to its realistic dimension and its ease of realisation.

The tests aim at enhancing people knowledge on raw earth, understanding the importance of the triphasic nature of earth material and identifying the best proportions of all material phases to reach its ideal properties. [4]

The test consists of a succession of combinations tests in which water content is varying regarding the solid components proportion. This will lead to different raw earth state : dry, humid or wet and plastic, solid, viscous or liquid.

The different samples are created mixing soil and water in a bucket, dosed with a graduate bucket and an electronic scale.

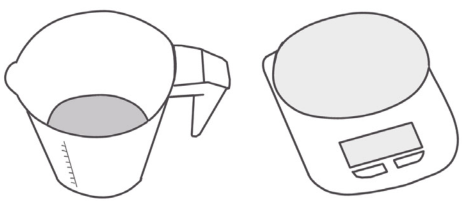

Fig. 9.3 - Tools for Carazas test

The earth used has a density d=1600 kg/m3 and for each sample a volume of 1000 mL is used. The mixture is either filled directly on a support, poured into wood mould of 10 x 10 x 10 cm or compressed. The moulds consist of 4 wooden boards attached to each other with filling screws, secured by bolts that can be easily removed to demould the samples.

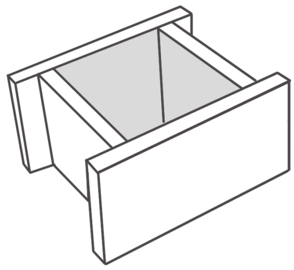

Fig. 9.4 - 10 x 10 x 10 sample for Carazas test

The samples are unmoulded and placed in a matrix divided into 15 boxes, corresponding to each sample proportion. The aim is to create a visual matrix to emphasize the relation between the three phases. Each sample will be correlated with specific air and water proportions depending on:

-The air component depending on the moulding of the sample : filled, pressed or compacted

- The water proportion influencing the final texture of the sample : dry, wet, plastic, viscous and liquid.

The results are obtained by visual interpretation of the appearance, the shape and the unmoulding.

2.b. Results analysis

The fifteen samples were placed into a matrix. Horizontally, the water percentage varies. Establishing the water proportion depends on the visual and tactile interpretation of the mixture. It enables to find a range for water proportion. For example, we established that the plastic state for this earth corresponded to 13% of water in volume while the liquid state corresponded to 39% in volume. Then, vertically, the pressure varies : no pressure just filling, then hand pressure and finally, pressure applied with a stick. This pressure results in creating samples with different heights, which variation has been calculated during the test. This variation of height, underlines the loss of porosity due to the compaction.

EXPERIENCE DATA				
	Earth (ml)	Water (ml)	Compressed by hand Height change (cm)	Compressed with a stick Height change (cm)
Dry	3500	0	-0,7	-1,8
Humid	3500	300	-1	-2,2
Plastic	3500	700	-4	-4,5
Viscous	4000	1700	0	-0,5
Liquid	4500	2800	0	0

Tab. 9.1 - Experience data

CALCULATED DATA				
	Water (%vol)	Water (%mass)	Compressed by hand Volume variation (m^3)	Compressed with a stick volume variation (m^3)
Dry	0	0	- 0,007	- 0,018
Humid	8,6	5	- 0,01	- 0,022
Plastic	20,0	13	- 0,04	- 0,045
Viscous	42,5	27	0	- 0,005
Liquid	62,2	39	0	0

Tab. 9.2 - Calculated data

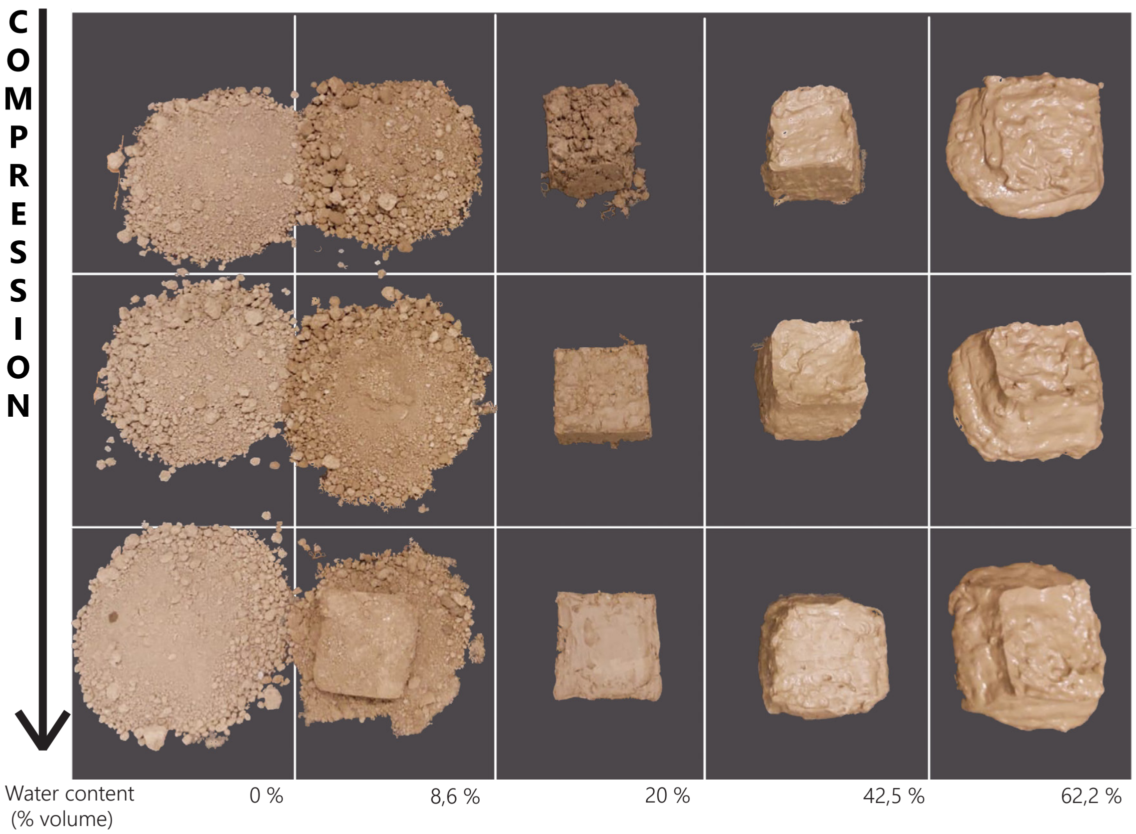

Fig. 9.5 - Carazas test

3. GRAVELS PROPORTION

3.a. Experimental process

In order to increase the bricks mechanical resistance, gravels were added to the mixture. Indeed as shown in different scientific articles [5], compressive and tensile strength increase up until a 20% aggregate content. Beyond this value, these strength decrease.

To test the best proportion of gravel we will create a matrix with 16 samples. Horizontally, the gravel content will vary (5%, 10%, 15%, and 20% of the soil volume) and vertically the water content will vary (15%, 20%, 25% and 30% of the soil volume). Material proportions will be evaluated with an electronic scale for the gravel or a measuring bucket for the water.

The gravel density is d=2544 kg/m3. It has been evaluated by first weighing a certain proportion and then pouring it into a certain amount of water to calculate the volume variation and thus deduce its volume. The mixture will be then mixed into a bucket, filled in the 10 x 10 x 10 cm wooden mould and then compacted with a wooden stick. The gravels come from the Quarry Spandri in Valmadrera in Italy. The gravels dimensions are between 2 and 6 mm.

3.b. Results analysis

Regarding the variation of water content, we notice that for a water proportion of 15%, the sample is easy to unmould, does not deform to the touch but crumbles. As the gravel quantity increases, the sample tends to crumble less.

For a content of 20% of water by volume, the sample is easy to demould, more compact and does not crumble. The resistance increases proportionally with the amount of gravel.

For 25% water, the sample sticks more to the mould when unmoulded and the variation in the quantity of gravel allows the brick to solidify but the sample is not resistant to the touch.

Finally, with 30% water, the material is more viscous and deforms when demoulded as it sticks to the sides of the mould.

Therefore, for the mixture of the bricks, we will use a proportion of 20% gravel in volume.

EXPERIENCE DATA					CALCULATED RESULTS		
Gravel (%vol)	Water (%vol)	Earth (ml)	Water (ml)	Gravel (ml)	Gravel (%masse)	Weight (kg)	Water (%masse)
5%	15%	1000	150	50	8%	0,12	9%
	20%	1000	200	50	8%	0,12	13%
	25%	1000	250	50	8%	0,12	16%
	30%	1000	300	50	8%	0,12	19%
10%	15%	1000	150	100	16%	0,25	9%
	20%	1000	200	100	16%	0,25	13%
	25%	1000	250	100	16%	0,25	16%
	30%	1000	300	100	16%	0,25	19%
15%	15%	1000	150	150	24%	0,38	9%
	20%	1000	200	150	24%	0,38	13%
	25%	1000	250	150	24%	0,38	16%
	30%	1000	300	150	24%	0,38	19%
20%	15%	1000	150	200	32%	0,5	9%
	20%	1000	200	200	32%	0,5	13%
	25%	1000	250	200	32%	0,5	16%
	30%	1000	300	200	32%	0,5	19%

Tab. 9.3 - Gravel test proportion

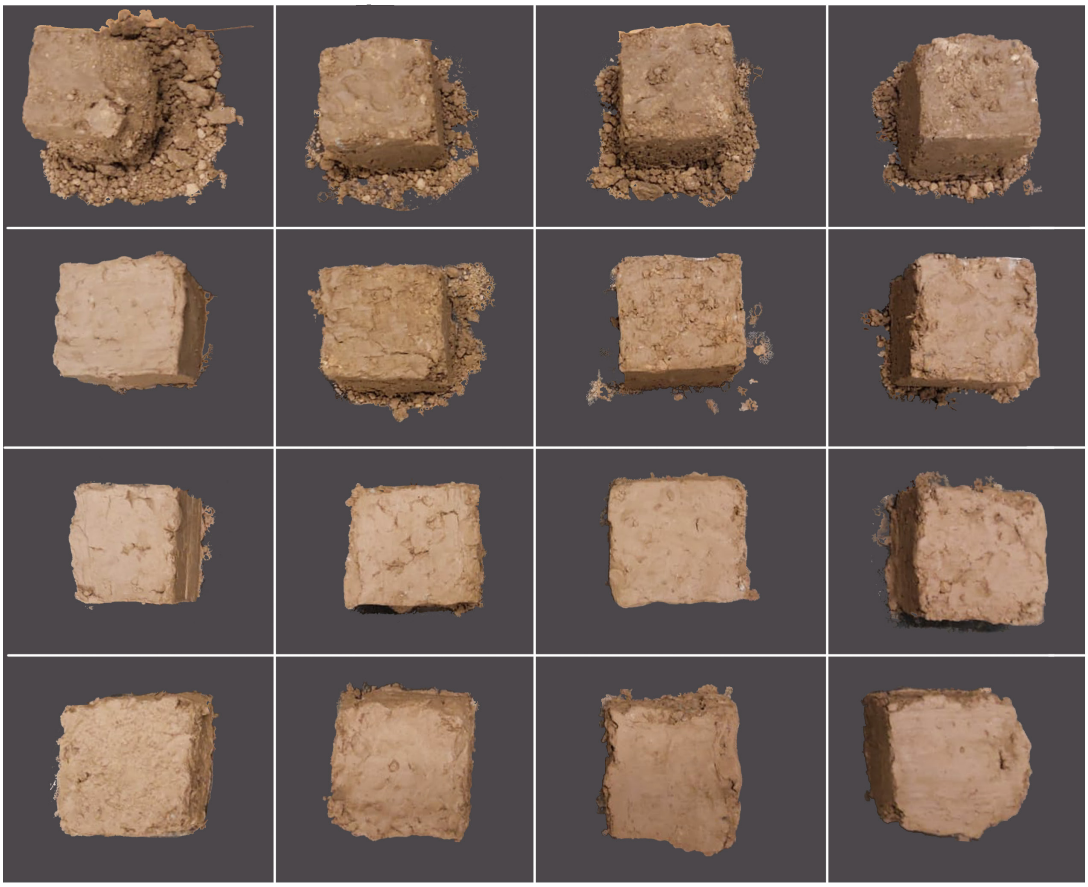

Fig. 9.6 - Gravel proportion test

4. MIX DESIGN

4.a. Objectives of the test

The aim of the mix design process is to identify the best proportion of fibres and water for the bio-bricks, turning thus raw earth into a building materials using the three phases involved in the material. As explained in §. III, raw earth is a three phase material, solid with minerals, liquid with water and gas with air. Each component in raw earth, fibres, water and air, interrelate with the others, play a role in the material and thus define the whole system organisation and strength.

The three phases will be manipulated and their proportions changed to create different raw earth samples that will be placed and compared in a matrix of 4 x 4 cells. The sample are identical, created with a unique wooden mould. During this test, information will be gathering throughout the while process. The operator experience such as the colour, the smell, the texture of each sample, need to be noted and are important for the final interpretation. Indeed, from it, we can understand which sample is the best suitable for construction based on its aspect, if it is fairly compact, humid... so it can be sued for the construction techniques involved.

Then, during the drying part, the operator needs to check several times the samples and takes notes of the way of drying, appearance of crack, the evolution of the shapes and the colour, the position of the grains...

4.b. Fibres

In order to identify the best solution suitable to Baghere's environment we will use fibres that can be found in the area and that can improve the mechanical resistance of the bricks.

The natural fibres chosen are Bamboo fibres, straw fibres and wood fibres

- **Bamboo**

Bamboo is a local plant harvested in Baghere and the Sedhiou region. It has already been used for centuries in the construction field in different continents. In Baghere, it is used mainly to create fences around settlements. It has noticeable mechanical properties and has the advantages to grow fast comparing to woods that could reach the same mechanical capacities.

Moreover, it contributes to the depollution process, as it captures polluted air during its growth. Finally, the creation and use of this building material will not only involve the craftmen but also the farmers growing it. It will have an impact on the population beyond just the construction workers.

The bamboo characteristics are :

Density ρ	700 kg/m^3
Specific heat	1,8 J/kg.K
Thermal conductivity	0,17 W/mK
Resistance to vapour diffusion	Tendency to reabsorb water
Dimensions	3 - 5 mm
Availability	Local
Environnemental impact	Low impact

Tab. 9.4 - Bamboo characteristics

Fig. 9.7 - Bamboo fibres

- **Straw**

We decided to test straw fibres for different reasons. Firstly, it is locally available in the region. Indeed as explained in the context analysis, there are cultivations of rice and cereals in Baghere. Thus, straw part could be used for construction purposes instead of being thrown away. Straw is alredy used in vernacular construction in sub-Saharan africa with the wattle and daub technique notably. Straw has great thermal properties and is used for insulation. Besides, in the literature review, it has been noticed that many bio-bricks experiences use straw fibres. Finally, as bamboo during its cultivation, it captures CO_2. Moreover, being a byproduct of agricultural activities, its environmental impact is greatly reduced. It is also available at low costs. [7]–[9]

The straw characteristics are:

Density ρ	58 kg/m^3
Specific heat	1900 J/kg.K
Thermal conductivity	0,06 - 0,094 W/mK
Resistance to vapour diffusion µ	1,15
Dimensions	3 - 5 mm
Availability	Local
Environnemental impact	Low impact

Tab. 9.5 - Straw characteristics

Fig. 9.8 - Straw fibres

- **Wood**

In Baghere region, different varieties of trees grow and are used for construction purposes. Thus, thinking of the waste management, we figured that the wood construction waste could be transformed into fibres to stabilise the bricks. Not only is this material local but it will also reduce construction waste. The wood used for the experience is a pine wood which is not found in Baghere region but it is similar enought to local woods. [10] Its characteristics are:

Density ρ	500 kg/m³
Specific heat	2300 J/kg.K
Thermal conductivity	0,1213 W/mK
Resistance to vapour diffusion µ	40
Dimensions	3 - 5 mm
Availability	Local
Environnemental impact	Low impact

Tab. 9.6 - Wood characteristics

Fig. 9.9 - Wood fibres

- **Fibres**

Research on different mix design processes enabled to identify the variation of fibres content that had to be tested . We also took into consideration the characteristics of each material such as their vapour diffusion resistance, their size... For example, the bamboo has a higher density which explains why its fibre content in mass is more important than the others. The proportions tested are:

Biomass	S1 % mass	S2 % mass	S3 % mass	S4 % mass
Bamboo	0,2	0,4	0,8	1,6
Straw	0,1	0,2	0,5	1,0
Wood	0,1	0,2	0,4	0,8

Tab. 9.7 - Fibres proportion in mix design

- **Water**

With Carasaz test we established an interval for water proportion around which water content in volume will change for the different sample. These water content are 10%, 20%, 25% and 30% in volume.

4.c. Experimental process

Mix design tests are performed at the laboratory of Building Recovery and Energy Efficiency at the territorial Pole of Politecnico di Milano in Lecco, Italy.

The following tools were used :

- Measuring bucket
- Electronic scale
- Bucket
- 10 x 10 x 10 cm wood mould with screws and bolts that can be easily removed to unmould the samples
- Wooden stick
- Gloves
- Working suits
- Sieve of 3 mm

In order to avoid lumps in the mixture, the earth is sifted. Then, the water, raw earth, gravels and fibres are weighed and poured into a bucket. The mixture is then filled in the 10 x 10 x 10 cm sample wooden mould and then compacted with a wooden stick. Each sample is then placed in a matrix to be compared with the other ones.

4.d. Results analysis

- **Bamboo**

With 10% water, we can see that for 0,2% fibre, the sample is very brittle, but as the fibre content increases in subsequent samples, the brittleness decreases. This underlines the fact that fibres play a role in the strength of brick.

At a water content of 20%, the samples remain unscathed during the demoulding and this process is easy. The samples are resistant to touch. They are compact overall, but at a fibre content of 1,6%, the sample is more brittle. This means that the fibres act as physical binders for the soil up to a certain level.

At 25% water, the samples are compact and resilient to the touch. However, they deform due to their plasticity. When demoulded, the sample sticks to the mould and becomes difficult to handle. Although their appearance is pleasing, this quantity of water cannot be retained for the bricks. In fact, this could lead to complications on site (bricks breaking during demoulding on site, etc.). In addition, increasing the water content of the bricks also increases the chances of cracking during drying.

Finally, with 30% water, the samples are too plastic, making demoulding complicated and deforming the brick at the same time. Once demoulded, the sample deforms and crushes on itself.

Thus, it was chosen to keep the sample with a 20% water content and 0,8 % bamboo content. The bamboo mix design is exposed in Fig. 9.10

Fig. 9.11 - A closer look on bamboo mix design

Fig. 9.12 - Work in progress

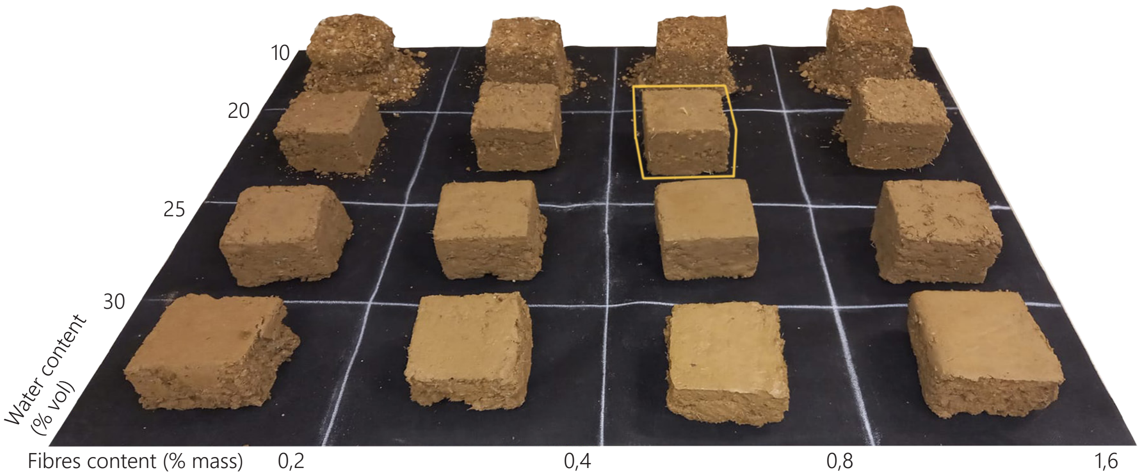

Fig. 9.10 - Bamboo Mix design

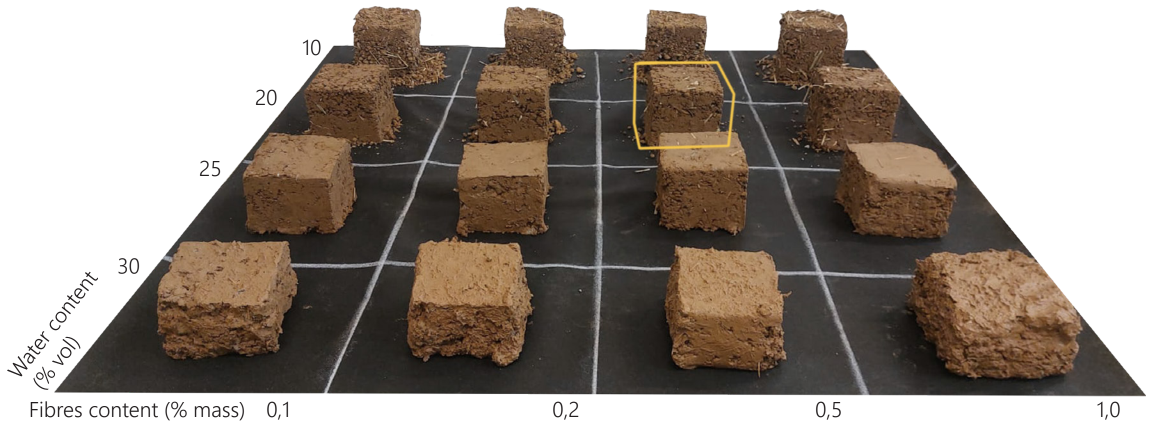

Fig. 9.13 - Straw mix design

- **Straw**

A 10% water content creates brittle bricks. As the fibre content increases, the brittleness is reduced but it is still too important to create a building material.

With 20% water content, the samples are firm and don't deform during demoulding. They are also compact and unyielding to the touch.

For 25% of water, even though samples look compact, unmoulding is complicated as the earth sticks to the samples. Moreover, once unmolded the mixture is too plastic and implies the risk for the bricks to be broken in two while transporting to the drying place for example.

For 30%, the samples themselves by crushing on themself while drying.

The proportions chosen for the straw bio-bricks are 0,5 % (in mass of earth) straw for 20% of water (in volume of earth)

- **Wood**

Once again we can notice that more fibres help the bricks to maintain their aspect when the water quantity is too low as it is for 10% water content.

Regarding the water, it acts as a binder and with its content increasing, the mixture becomes more plastic, malleable and uniform. For exemple from 25% water content, the samples are difficult to unmould and deform themselves.

Thus, the proportions chosen for the wood fibres compressed bricks are 0,4% of fibres (in mass of earth) and 20% of water (in volume of earth).

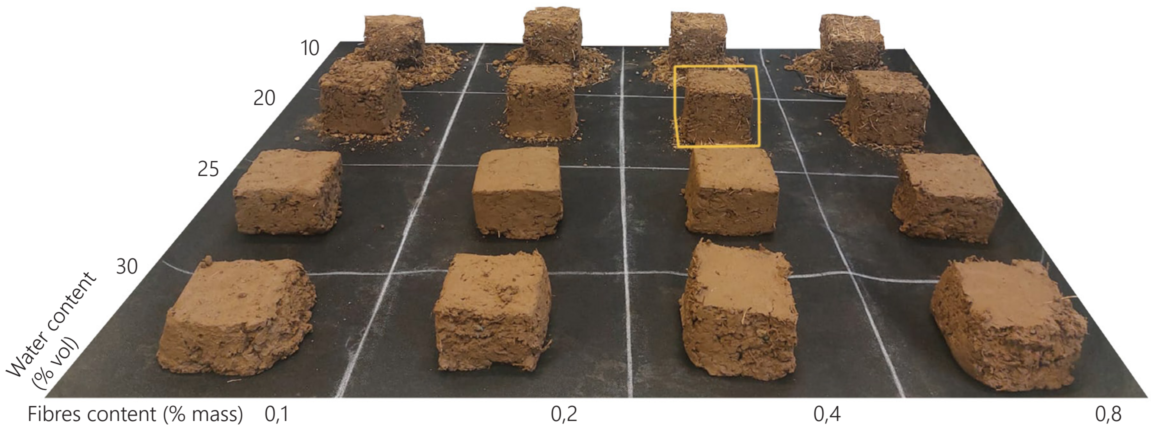

Fig. 9.14 - Wood mix design

5. Creation of samples

5.a. Creation of earth bricks

For the erosion test, bricks were created with a Cinva Ram press. Indeed, not only does it create bricks with dimensions close to the standards, but it also provides a high compression pressure manually. The dimensions of the stamp are 28 x 14 x 12 cm. To reach our project dimensions as much as possible, we used a wooden plank of 3 cm high. Finally our bricks had dimensions of 9 x 14 x 28 which is close to 9 x 14 x 29,5 cm, the project dimensions. The load to which the bricks were submitted was applied on the brick surface 14 x 28 cm, hence 392 cm².

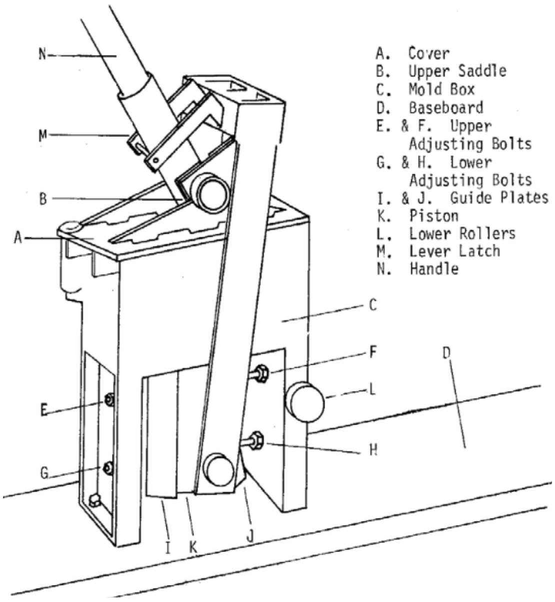

Fig. 9.15 - The CINVA-Ram Block Press and its parts @John R. Hansen

Raw earth must be first sieved using a 3 mm sieve. Indeed, this process is aimed at avoiding agglomerates of earth that will create lumps in the mixture and thus decrease its mechanical characteristics. Then, in a large bucket, raw earth, gravels and fibres are mixed. The water is then slowly added to avoid the creation of lumps. The mixture consistency should be slightly grainy but should stick together when pressed in the hand.The mixture is then poured in the mould of the press. The mould is oiled with a fabric to facilitate the extraction of the brick. Using the lever latch, the earth is compressed. Then the cover is removed to extract the brick with the lever latch.

Regarding the pressure applied, some experience limits are reached. Indeed, as explained in §. III, the compressive resistance of the compressed earth bricks relies on the force applied on the brick during its production. In literature [12], a minimum pression of 5 kg/cm² is required. Taking in consideration the brick surface and no lever latch, a weight of 1960 kg should be applied. Thus, a lever latch is necessary to reach the minimum pressure needed. In our experience a 3 m lever latch is used. Considering a weight of 70 kg, the force of the worker $\overrightarrow{F_w}$ and its moment involved $\overrightarrow{M_w}$ can be calculated. Thus F_w = 690 N and M_w = 2060 N.m. The press can be assimilated to the following system :

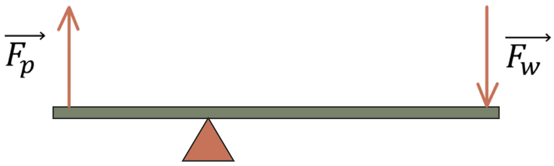

Fig. 9.16 - Functional diagram of a lever

Using the equilibrium of the moments M_w=M_p with M_p = F_p*l_p , F_p = M_w/l_p ,where l_p = 50 cm thus F_p = 4120,20 N, which give a conception pressure of P_p = 1,07 kg/cm². To reach the required force different solutions can be applied :

- Using a longer latch arm
- Increasing the applied weight
- Reducing the brick surface

5.b. Creation of cylindric samples

To create the samples that will be used for compression tests, we used another manual press as shown in fig. 9.19. With the cylindric stamp, samples of 10 cm diameter are created. Dimensions were chosen based on different experiences read in different scientific articles. [11] [13]

The surface of the samples is 0,0314 m² and the lever latch 1,10 m. Thus, considering a weight of 70 kg, F_w = 690 N and M_w = 755,37 N.m. The press can be also assimilated to the system in Fig. 9.17. Using the equilibrium of the moments M_w = M_p, F_p= 3776,85 N, which give a conception pressure of P_b = 4,90 kg/cm².

The pressure is almost the one required and can be reached since the surface of compression is smaller. For 72 kg, the minimum pressure required is reached. Thus, the cylinders created for compression tests are reliable regarding compressed earth bricks standards.

Fig. 9.17 - Step 1 : Sieving of the soil

Fig. 9.18 - Step 2 : Creation of the mixture

Fig. 9.19 - Step 3 : Filling of the Cinva Ram press mould

Fig. 9.20 - Step 3 : Filling of the cylinder press mould

Fig. 9.21 - Step 4 : Compression of the raw earth

Fig. 9.22 - Step 4 : Compression of the raw earth

Fig. 9.23 - Step 4 : Extraction of the brick

Fig. 9.24 - Step 4 : Extraction of the cylinder sample

5.c. Drying process

Regarding the drying process, samples first dried outside under the sun. To check their drying, their weight is measured every two days. In the first day, the bricks lost around 100 g of water per day, then this value decreased until it reached less than 1 g. The process is considered done when mass variation is less than 1 g.

The cylinders samples were dried outside under the sun and then in a room for 30 days to avoid the outside humidity. The bricks were also left for 21 days outside but then dried in the oven for timing reasons. Indeed, in the Literature review, experiences has shown that the drying process does not significantly impact drying in an oven under 80°C does not significantly change the bricks characteristics. [15] The bricks were put in an oven at 60 °C for an hour with regular weigh check.

Fig. 9.25 - Drying of the bricks and samples

6. Erosion test

6.a. Experimental process

The test is performed to determine the resistance and the durability of bio-based bricks when subjected to rainwater. Indeed, as the building is located in a tropical area, it is important to test it to anticipate the eventual issues and to foresee the maintenance.

The following tools are needed :

- Measuring bucket
- Flexible tube
- Timer
- Wood support
- Ruler
- Hammer
- Chisel
- Three brick samples of each fibre

The test consists in dripping water in a regular way on a brick sample to calculate the depth of the erosion caused. To do so, first with a flexible tube and a 100 mL graduate bucket, a water regulation system is created. It will enable to dispense 100 mL of water on a period of time between 20 to 60 min. Our dripping time was 26 min 18 s. The dripping starts at 250 mm height from the brick surface. The brick is positioned with an angle of 27°.[12] The test ends when the 100mL water quantity has been consumed.

From it, the depth D of the erosion hole is calculated. Then, the brick sample is broken into to two parts with the hammer and the chisel in the centre to measure the humidity penetration U. With these values calculated in mm, we can refer to the erosion table to find the corresponding erosion index.

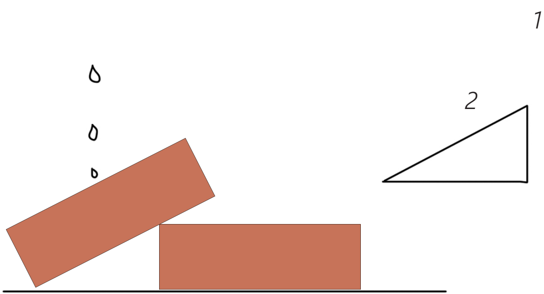

Fig. 9.26 - Erosion test @Manuale della terra cruda

Fig. 9.27 - Wood bricks after erosion test

6.b. Results analysis

Measuring the depth D of the whole created by the dripping of 100 mL of water and the depth U of the humidity penetration, the erosion status and class can be identified. The three types of bricks are all in Class 3.

However we notice that straw fibres stabilised bricksresist better to direct water exposition then comes bamboo and wood. Regarding the humidity absorption, bamboo fibres bricks are the best one. This can be explained by the capacity of bamboo to reabsorb water. All bricks have then a erosion status that is accepted.

Therefore, if bricks are well separated from humidity owing to the laterite stone fondations and well protected from the rain with the long edged roof, they should resist erosion over time.

Property	Criteria	Class
Hole's depth D (mm)	0 < D < 5	2
	5 ≤D < 10	3
	10 ≤ D < 15	4
	D > 15	5 (not accepted)
Depth of moisture penetration U (mm)	< 120	Accepted
	≥ 120	Not accepted

Tab. 9.8 - Erosion test interpretation @Il manuale della terra cruda

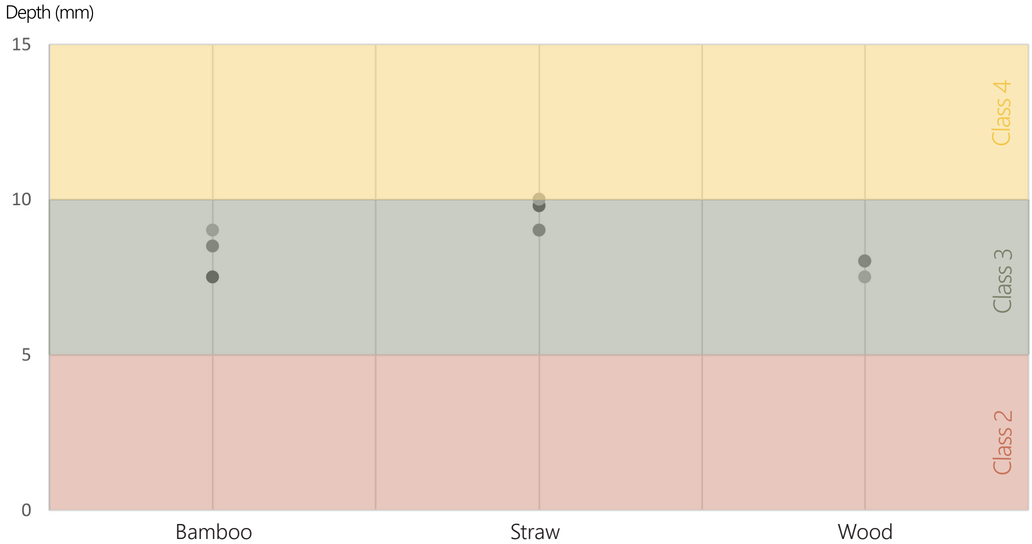

FIg. 9.28 - Comparative chart of erosion depth

Material	Mean Depth D	Erosion Index	Mean Penetration U	Erosion status
	mm	From 2 to 5	mm	U < 120 mm
Bamboo	8,3	3	21	Accepted
Straw	9,6	3	26,6	Accepted
Wood	7,8	3	24	Accepted

Tab. 9.9 - Erosion results

7. Compression test

7.a. Experimental process

The aim of the mechanical test is to highlight the impact of fibres in the mechanical performance of the bricks. Three samples of each type of fibre will be tested. Due to the small number of samples, this test doesn't claim to classify the material. The compressive strength of each type of bio-bricks will be compared between them but there will also be compared to the one defined by Cycle Terre standards.

Mechanical tests are performed at the laboratory of Concrete materials and structures at territorial Pole of Politecnico di Milano in Lecco, Italy.

Cylinders of 18 cm height and 9,5 cm diameters are tested. The load surface is 78,675 cm^2. For each type of fibre, three identical samples are tested. To have reliable results, the surface of the sample must be very plane. Thus, all samples were cut and then smooth with sand paper. Tests were performed with a compressive machine CONTROLS, Model 65 - L120/*. Samples were submitted to direct centred uniaxial compression and placed between two compression plates of 165 mm in diameter. The load rate is 0,600 MPa/s.

With the maximum forces applied, the ultimate compressive strength can be calculated as $\sigma = F/S$.

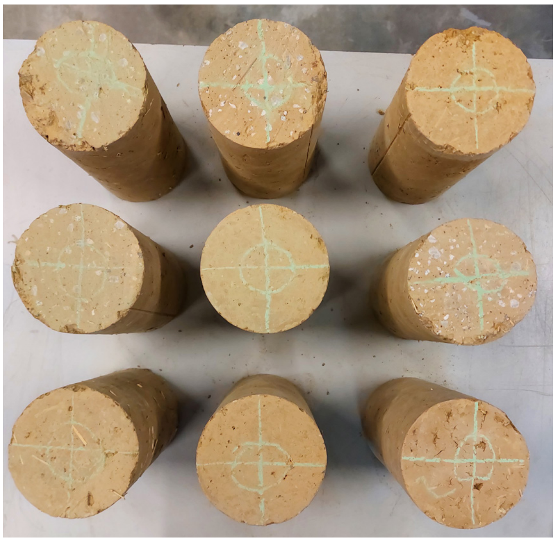

Fig. 9.29 - Samples chosen for compression test

7.b. Results analysis

The failure of the bricks in compression are defined by a mixed cracking pattern with parallel and diagonal cracks respecting the uniaxial loading direction. The first cracks appear before reaching the maximum load. The type of failure is classified as R7 regarding the concrete failure tipology.

From a certain load, the sample tends to deform and expand laterally. Its diameter increasing at the centre until the first vertical and diagonal cracks appear.

We can notice that the cracks arrive sooner for wood samples then come straw samples and then bamboo samples. Regarding compression resistance, it is the bamboo reinforced samples that have the higher resistance followed by straw samples and wood samples. The bamboo fibres were the most rigid fibres followed by straw and then wood. This aspect may have improved the fragile behaviour of raw earth material regarding cracks formations. Indeed, one of the fibres roles is to hold back cracks and thus distribute the load arriving on it.

Knowing the ultimate compressive stress of each sample, the average compressive strength f_{cm} strength is calculated.

These values can be compared to the ones found in Cycle terre standards. Samples could be assimilated to a CEB 20 which has an average compressive strength of 2,0 MPa and used for building purpose. In order to classify the material and determine a characteristic compressive strength value, a minimum number of 100 samples should be tested.

Fig. 9.30 - Diagonal and parallel cracks for CB1

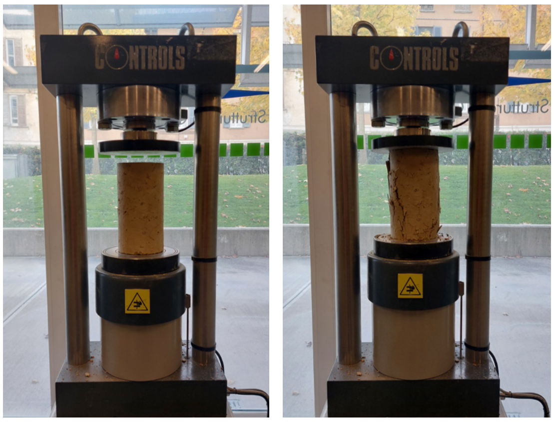

Fig. 9.31 - Before and after compression test for CB1

CB 1	
Diameter [mm]	95
Height [mm]	180
Weight [kg]	2,546
Volume [m^3]	$1{,}28.10^{-3}$
Density [kg/m^3]	1995,5

Tab. 9.10 - Dimensions of CB1

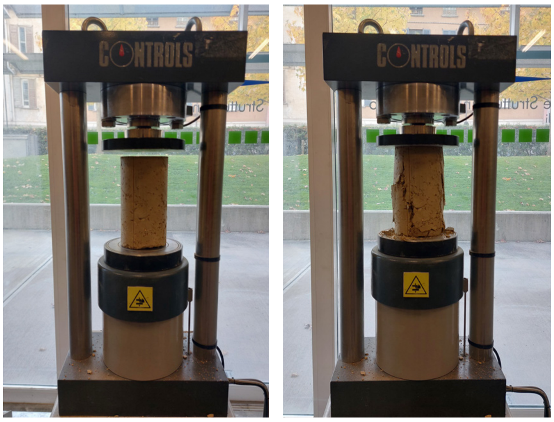

Fig. 9.32 - Before and after compression test for CB2

CB 2	
Diameter [mm]	96
Height [mm]	181
Weight [kg]	2,559
Volume [m^3]	$1{,}31.10^{-3}$
Density [kg/m^3]	1953,26

Tab. 9.11 - Dimensions of CB2

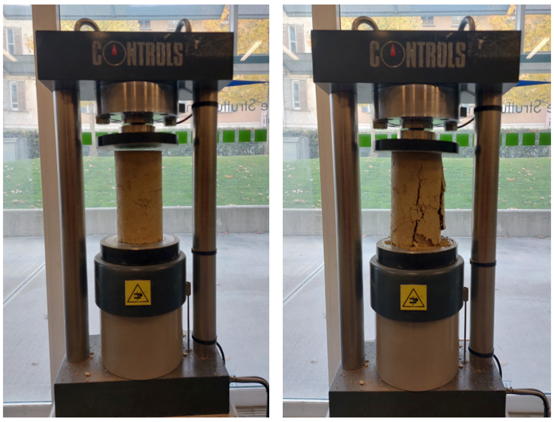

Fig. 9.33 - Before and after compression test for CB3

CB 3	
Diameter [mm]	95
Height [mm]	181
Weight [kg]	2,574
Volume [m^3]	$1{,}28.10^{-3}$
Density [kg/m^3]	2006,29

Tab. 9.12 - Dimensions of CB3

N° test	Maximum load [kN]	Maximum stress [kN]	Average stress f_{cm} [kN]
CB1	17,35	2,45	2,46
CB2	17,03	2,35	
CB3	18,19	2,57	

Tab. 9.13 - Compression tests results for bamboo bio-bricks

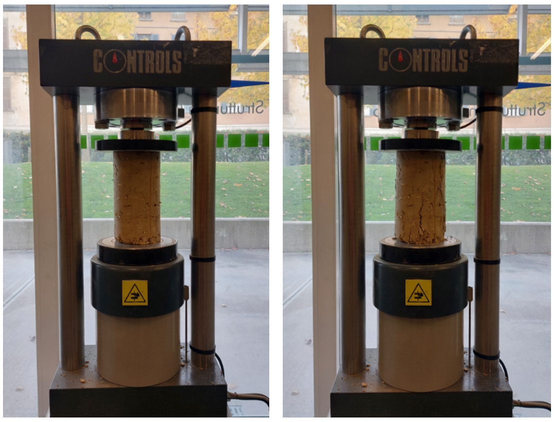

Fig. 9.34 - Before and after compression test for CS1

CS 1	
Diameter [mm]	95
Height [mm]	181
Weight [kg]	2,606
Volume [m^3]	$1,28.10^{-3}$
Density [kg/m^3]	2031,23

Tab. 9.14 - Dimensions of CS1

Fig. 9.35 - Before and after compression test for CS3

CS 3	
Diameter [mm]	95
Height [mm]	190
Weight [kg]	2,699
Volume [m^3]	$1,35.10^{-3}$
Density [kg/m^3]	2004,07

Tab. 9.15 - Dimensions of CS3

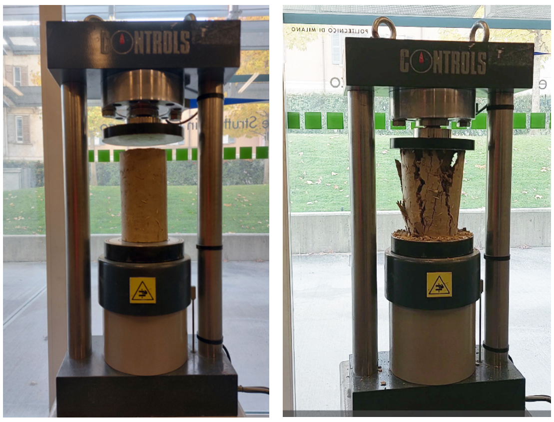

Fig. 9.36 - Before and after compression test for CS6

CS 6	
Diameter [mm]	95,5
Height [mm]	180,5
Weight [kg]	2,632
Volume [m^3]	$1,29.10^{-3}$
Density [kg/m^3]	2035,69

Tab. 9.16 - Dimensions of CS6

N° test	Maximum load [kN]	Maximum stress [kN]	Average stress f_{cm} [kN]
CS1	18,01	2,54	2,38
CS3	16,00	2,26	
CS6	16,69	2,33	

Tab. 9.17 - Compression tests results for straw bio-bricks

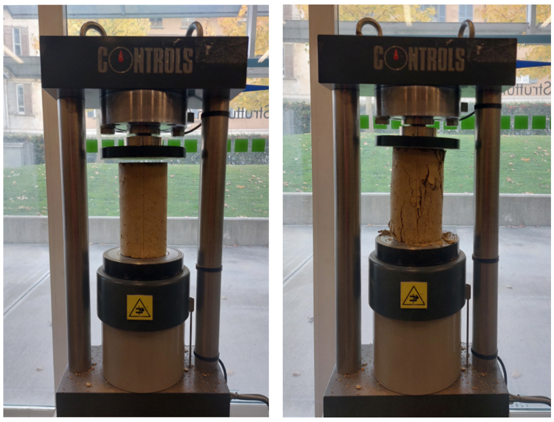

Fig. 9.37 - Before and after compression test for CW1

CW 1	
Diameter [mm]	95
Height [mm]	180
Weight [kg]	2,536
Volume [m^3]	$1,28.10^{-3}$
Density [kg/m^3]	1987,65

Tab. 9.18 - Dimensions of CW1

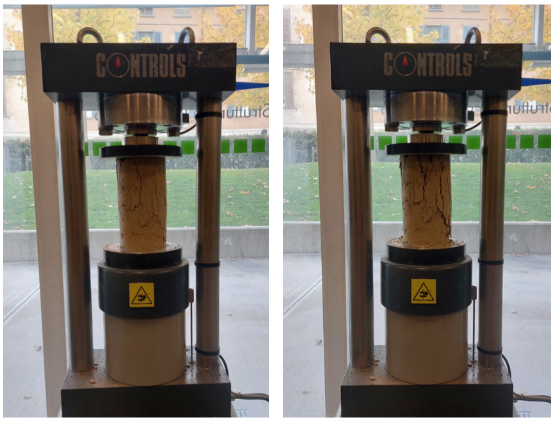

Fig. 9.38 - Before and after compression test for CW2

CW 2	
Diameter [mm]	96
Height [mm]	180
Weight [kg]	2,553
Volume [m^3]	$1,30.10^{-3}$
Density [kg/m^3]	1959,50

Tab. 9.19 - Dimensions of CW2

Fig. 9.39 - Before and after compression test for CW5

CW 5	
Diameter [mm]	95
Height [mm]	180
Weight [kg]	2,579
Volume [m^3]	$1,28.10^{-3}$
Density [kg/m^3]	2021,35

Tab. 9.20 - Dimensions of CW5

N° test	Maximum load [kN]	Maximum stress [kN]	Average stress f_{cm} [kN]
CW1	16,08	2,27	2,16
CW2	15,63	2,16	
CW5	14,57	2,06	

Tab. 9.21 - Compression tests results for wood bio-bricks

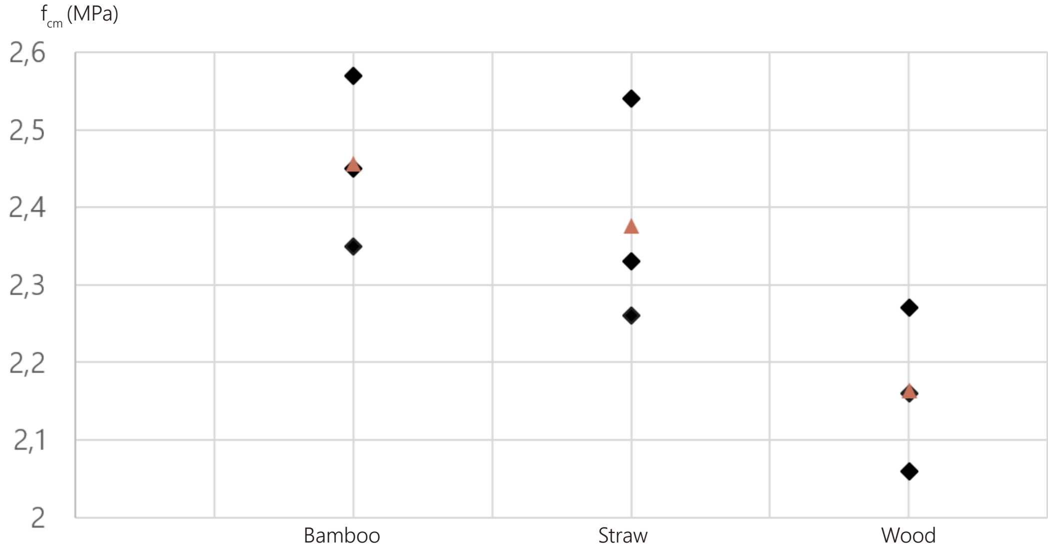

Fig. 9.40 - Comparative compressive stress chart

Once the average compressive strength of the samples has been determined, it can be compared to the German earth building standards DIN 18945 (2013-08)[16] [17]. Again, due to the low number of samples, the material can't be classified but only an estimation of its classification can be suggested. Thus, all bio-bricks correspond to a compressive class CS 2 based on the smallest single value. CS 2 is the minimum class required for load-bearing situations [18] [19]

Compressive strength Mean value (MPa)	Compressive strength Smallest single value (MPa)	Class of block compressive strength CS
σ > 5,0	σ > 4,0	CS 4
3,8 < σ < 5,0	3,0 < σ < 4,0	CS 3
2,5 < σ < 3,8	2,0 < σ < 3,0	CS 2

Tab. 9.22 - Compressive strength classes (CS) for earth blocks @ DIN 18945 (2013-08)

8. Conclusion

The results of the experiences sets a dataset to interpret the results from a qualitative and quantitate point of view and propose explanation on the mechanical properties of the brick.

With the granulometric test, we identified the composition of the soil used. Then, with the erosion test, we highlighted the durability of the brick when exposed to the rain. The three types of bricks are classified Class 3 and can then be used for building purposes. More precisely, straw bio-bricks has the best resistance to direct water exposition then comes bamboo bio-bricks and wood bio-bricks. Regarding the humidity absorption, Bamboo bio-bricks are the best one. This can be explained by the capacity of bamboo to reabsorb water. Therefore, if the bricks are well separated from humidity and well protected from the rain they can resist erosion over time.

Finally, the static test emphasized the role of natural fibres and their mechanical properties. We can state that bricks are sensitive to the applied forces and as concrete, they resist better in compression than in tension. The fibres could play a role in increasing the compressive strength. This is explained by the fibres interactions with the material that not only reduce shrinkage cracks but also seem to enhance the material ductility. This is very useful during the production process but also on the long term to resist to external loads. Comparing the statics results for the different types of fibres used, we can state that bamboo fibers reinforce better regarding its compressive stress, then come straw and wood. Bamboo fibres were the most dense, and rigid out of the fibres tested. These two parameters could explain their performance.

Hence, bamboo bio-bricks will be used in the project.

X. LIFE CYCLE ASSESSMENT

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1. LCA METHODOLOGY

1.a. LCA definition

The ISO 14040 defines the LCA as follows: LCA studies the environmental aspects and potential impacts throughout a product's life (i.e. cradle-to-grave) from raw material acquisition through production, use and disposal. The general categories of environmental impacts needing consideration include resource use, human health, and ecological consequences. [1]

The idea of the Life Cycle Assessment was invented in the 60's when concerns about limited access to resources and degradation of the environment started arising. The methodologies and softwares emerged mostly during the 80's and 90's through international scientific collaboration. The first international standard on LCA practice, ISO 14040, was published in 1997. It defines the framework for Life Cyle Assessment and was followed by three other standards: ISO 14041, ISO 14042 and ISO 14043 detailing the stages of this framework.

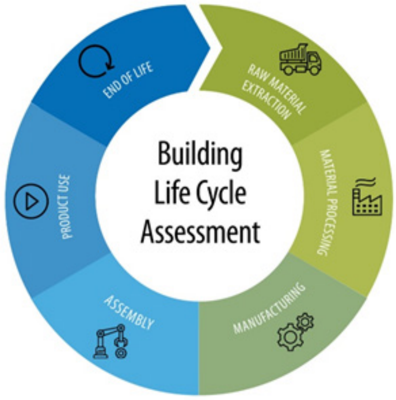


Fig. 10.1 - Life cycle phases @Noncrete

- **Defining characteristics**

Some defining characteristics of Life Cycle Assessment are:

- Taking a life-cycle perspective

The LCA should consider the life cycle of a product. This means that the environmental impacts of the production, transport, use and discarding, or transformation in the case of recycling, should be computed. This avoids burden shifts between life cycle stages.

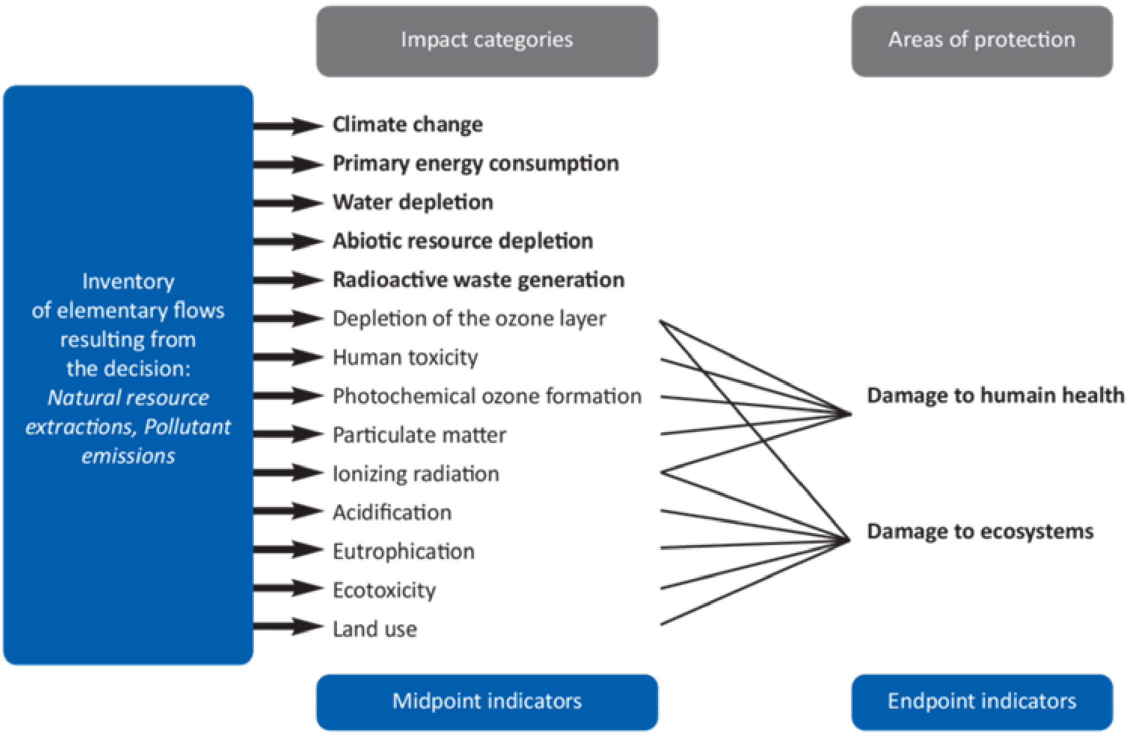


Fig. 10.2 - Impact categories of LCA @S.Maran

- Covering several environmental issues

The Life Cyle Assessment is meant to cover different environmental impacts. Once again, the objective is to avoid burden shifting by considering resources depletion, climate change but also damages to human health and to ecosystems. This ensures that the impact of the product on one aspect isn't lowered to the detriment of another.

- Being quantitative

The LCA produces quantitative data in the aim of allowing for comparison between products or production processes.

- Being based on Science

The quantification of potential impacts is rooted in scientific work. Flows are usually based on measurements and relationships between emission and impact are based on scientifically proven casualties. On top of this scientific data, LCA requires value judgement when assigning weights to different products or processes.

- **Strength and limits**

LCA has both advantages and limits. First, it allows the comparison of environmental impacts of complex product systems made of numerous processes. This strength can also be a weakness due to the simplification and generalization required. This is why LCA does not calculate real impacts but impact potentials. Another limit is that LCA uses an estimated impact of each process and does not account for rare problematic events like marine oil spills or industrial accidents.

Another limitation often overlooked is that LCA enables to compare different processes or products to state which one is more environmentally friendly. However, LCA cannot give an absolute measure of sustainability: it cannot specify whether this product can be maintained in the future as it is today without compromising future life conditions on earth. [2]

1.b. Framework

Two international norms define the framework for LCA: ISO 14040 and ISO 14044 EN-15978. The method of assessment is made of four steps : goal and scope definition, inventory analysis, impact assessment and interpretation.. However, the process is made to be iterative with a lot of coming back and forth between stages.

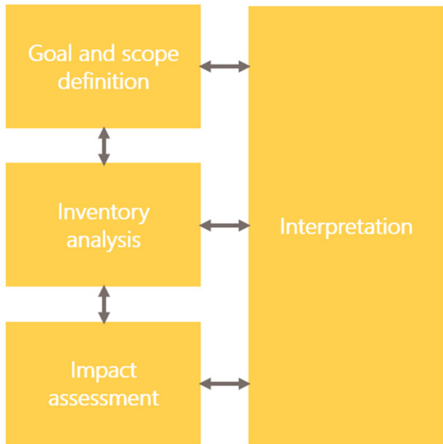


Fig. 10.3 - LCA Framework @JRC-IES

- **Goal and scope definition**

The first step is the Goal and scope definition. The goal definition aims at setting the objectives of the study, and thus justifying choices made in the analysis. It should clarify the method choices, assumptions and the impacts covered by the study.

The scope definition should disclose the functional unit and reference flow. The functional unit is the quantitative description of the product or service being assessed, for example, 1 m² of wall. It scales the whole inventory of processes.

The scope definition also defines the boundaries of the study in terms of stages of the life cycle: cradle-to-grave, cradle-to-gate, gate-to-gate, as illustrated in Fig.10.4. Scope definition also includes the definition of cut-off, which will be explained in the next section, the methods used for quantification of the processes, the data sources and quality and the format of the planned reporting.

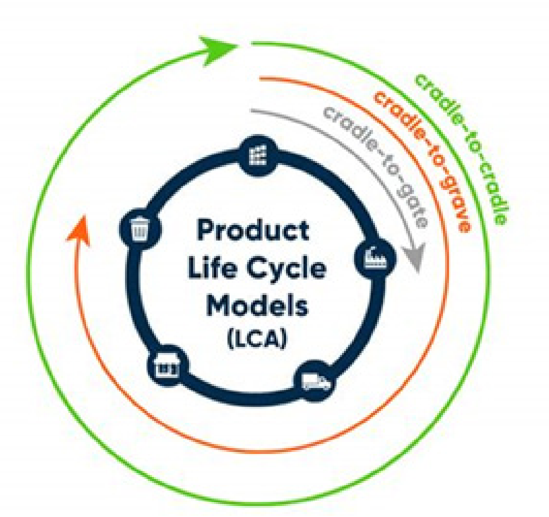


Fig. 10.4 - System boundaries @ecochain

- **Inventory analysis**

The second step, the inventory analysis, consists in listing and quantifying all the unit processes involved in the life cycle of the functional unit. To identify the complete inventory of processes, it is recommended to draw inspiration from similar existing studies and product declarations.

Each process concentrates various flows, whose potential impacts have to be summed to find the potential impact of the process. The different types of flows concerning a unit process are illustrated in FIg. 10.5. Life Cycle Inventory databases already provide potential impact for different unit processes.

In this stage, the list of all the data used for each unit process is also being established. The data sources need to be selected and the datasets corresponding to the processes have to be extracted and potentially weighed or calculated. This step also involves the modelling of reuse, recycling, and recovery processes.

- **Impact assessment**

The third step is the impact assessment. During this stage, the data for each process is computed based on the Life Cycle Inventory to obtain quantitative potential impact. The results should be then reviewed as well as the sensitivity, completeness, and consistency of the study, to check if there are not any issues.

Based on the obtained results, more iterations can be made, and the previous steps can be revised. The study boundaries, the data sources, the cut-off methodology or list and quantification of unit processes are all parameters that can be adjusted in different iterations.

- **Interpretation**

Finally, the interpretation consists in drawing conclusions according to the goals of the study. It can be a comparison, a list of recommendations or a declaration of potential impact.

The limitations of the study should be addressed in this part, as well as possible focus points for future work on the subjects to further the conclusions.

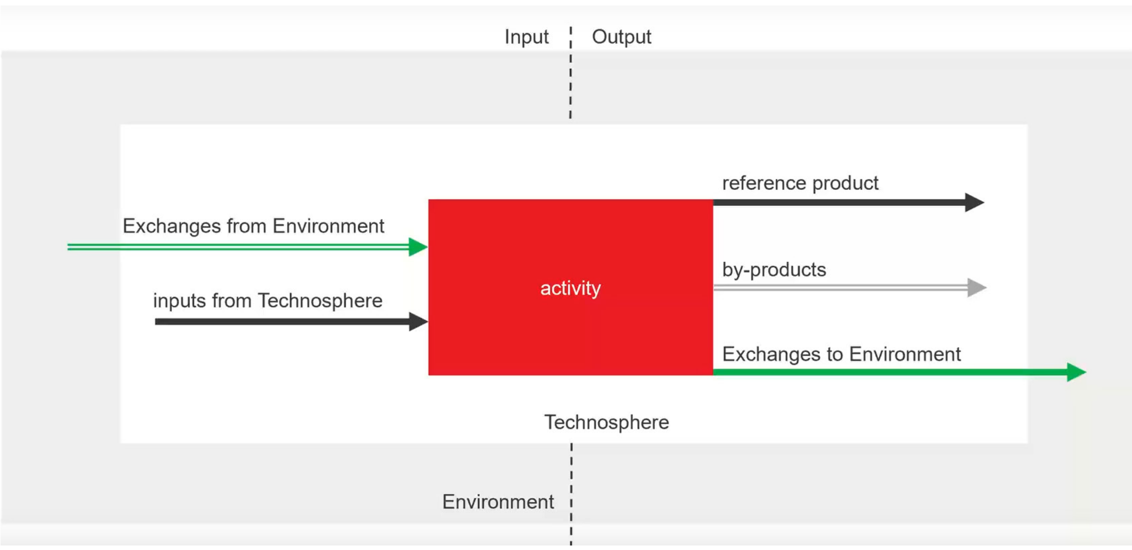


Fig. 10.5 - Unit process diagram @ecoinvent

1.c. Data sources

For this study, we used two main databases: ecoinvent and OneClick LCA.

- **Ecoinvent**

Ecoinvent is a not-for-profit association based in Switzerland, dedicated to the availability of data for sustainability assessments worldwide. The ecoinvent Database is a Life Cycle Inventory (LCI) database. It contains more than 10 000 'datasets', modelling human activities or processes. The ecoinvent Database is updated annually. [4] For this study we used the ecoinvent version 3.4 providing the IPCC Global Warming Potential of each dataset. The datasets are allocated to a specific region of the world. For Senegal, no specific data is provided, and the data computed in our analysis is the one provided for "Rest of the World".

The ecoinvent database mostly provides data on raw materials and simple flows. It provides the potential impact of activities of transformation, of transport, of waste treatment, but does not provide the whole impact of a product life cycle. It will be used to calculate the LCA of the bio-bricks, enabling the computation of each flow of the life cycle according to our specific product composition, detailed in part IX, and geographical setting in Baghere, Senegal. The ecoinvent database will also serve in the impact assessment of all non-conventional building products used in the building project LCA such as earth-based materials, stone, or straw.

- **Oneclick LCA**

OneClick LCA is a firm founded in 2001 in Finland. The software of the same name is made for computing LCA of building and infrastructure projects. The data accessible in the software One Click LCA comes from different databases of EPDs.

An EPD is an Environmental Product Declaration defined by the ISO 14025, ISO 21930 and the amended EN15804 standards. It is a verified impact estimation for a given product, usually computed by industrial producers or governmental organizations.

One Click LCA also has its own database of EPD compliant with European and international standards. In areas where there is no comprehensive building LCA database available, such as in Senegal, One Click LCA offers localized data calculated through a local compensation methodology to match the local manufacturing conditions. [5] In short, building products LCA are already available in the One Click LCA databases, where all the life cycle stages detailed in Fig. 10.6 are computed. These databases will be preferred for more conventional building products, where the transport distance will be adapted to our geographical context.

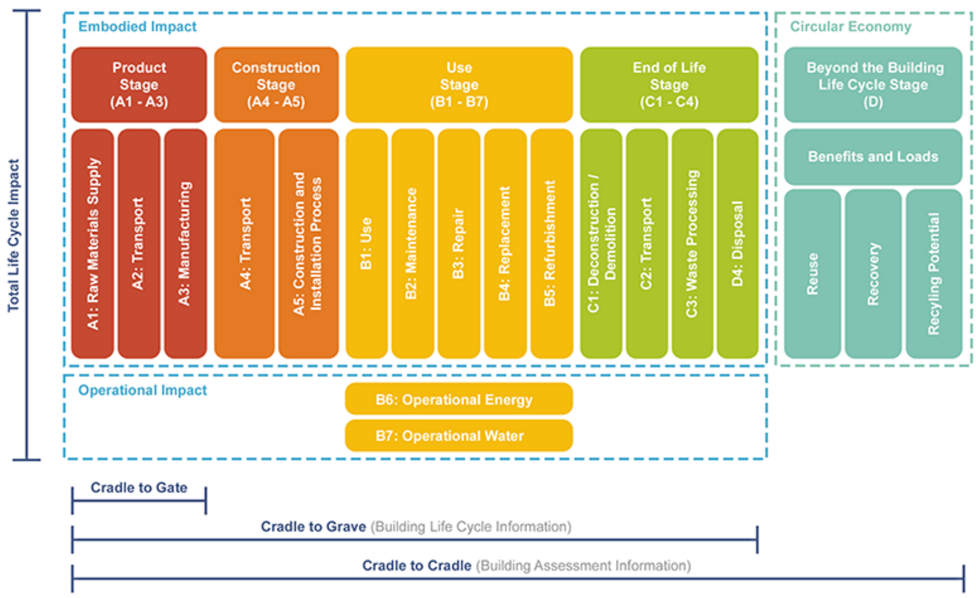


Fig. 10.6 - Stages considered in a building LCA @EN 15804

1.d. Modelling reuse and recycling

Reuse is defined as the use of products or components more than once for the same, or other purposes, without reprocessing according to the ISO 20887 standard. The same standard precises that recycling involves reprocessing, which enables materials or parts to be separated and used as material input for same or different use.

Both processes are inherent to circular economy and allow materials to prolongate their life cycle avoiding extraction of new resources. However, reuse should be preferred to recycling as it consumes less resources for the transformation between two uses. Indeed, the European Waste Framework Directive specifies a waste hierarchy: Prevention, Reuse, Recycle, Recovery, and Disposal.

Modelling recyclable and recycled products in LCA can be done in different ways. The method used in this study is the allocation cut-off by classification. This model is used in the European normative EN15804.

Cut-off allocation means that all the emissions of the sorting and recycling process are allocated to the producer of the initial product. The waste producer doesn't receive any bonus from the fact that the waste is to be recycled or reused. It follows the principle of "polluter pays". The recycled or reused product is considered with a zero environmental impact of production when employed in a new project. Only the transport and end of life of the product are considered in the environmental impact. [8]

1.e. Modelling biogenic carbon

- **Vegetal products and carbon storage**

Vegetal products have a capacity to store carbon. During their growth, plants can absorb carbon dioxide (CO2) from the atmosphere through the process of photosynthesis. Carbon is fixed in the plant but also in the soil. Carbon stored is referred to as biogenic carbon. When plant dies, during the decomposition of the vegetal matter, carbon is released in the atmosphere in the form of CO_2 and CH_4, two green house gases.

When wood products or vegetal fibres are employed in a building, carbon contained in the plant is stored in the building, while new vegetation can grow. The decomposition is delayed by using vegetal products in construction. In the natural cycle, carbon would be emitted by decomposition of the old tree while a new tree grows making the whole process carbon neutral. The storage of carbon in buildings allows a decrease of the atmospheric carbon if the vegetation is consistently being replanted. This concept is illustrated in Fig 10.8.

We therefore understand that fast growing species are an advantage for this phenomenon. Indeed, during the carbon storage of the buildings, they will be able to grow more times and therefore stored multiple times carbon in products. The time between two plantations is called the rotation period of the species. The lower this period is, the more efficient the carbon storage with this species.

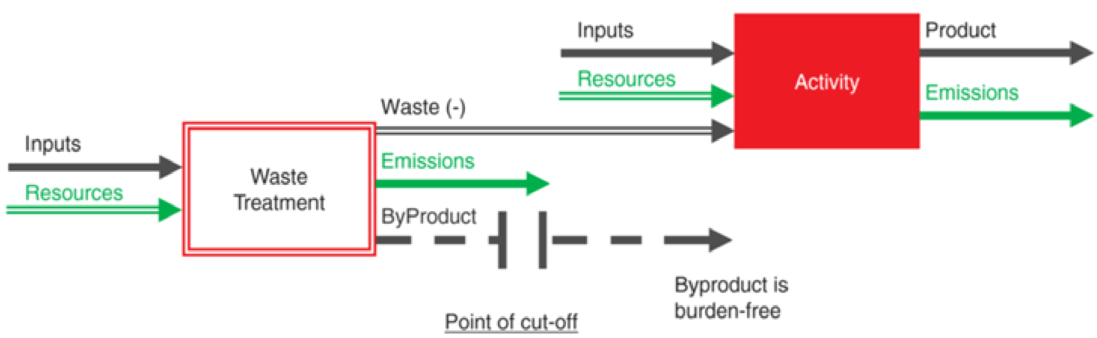


Fig. 10.7 - Cut-off allocation diagram @ecoinvent

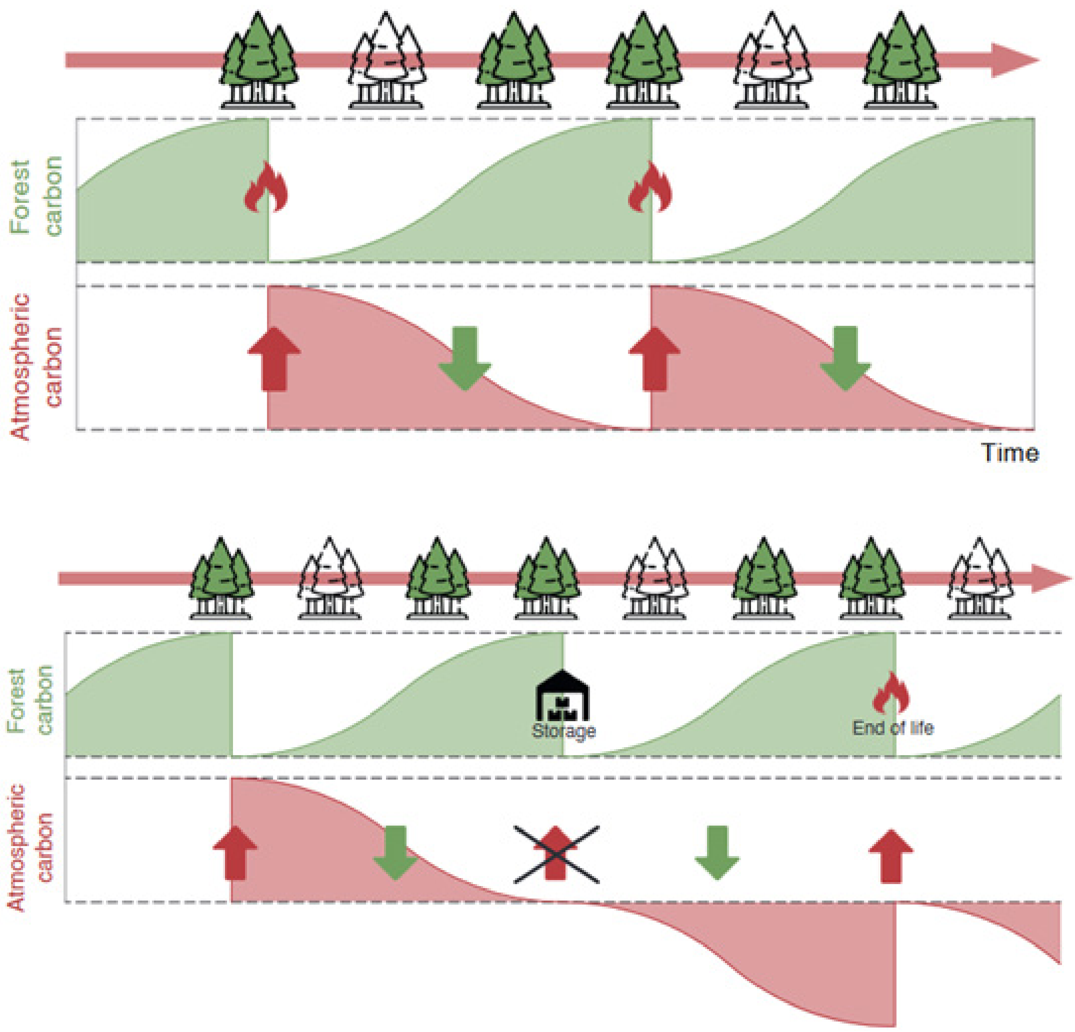


Fig. 10.8 - Carbon storage in biomass @E.Lannoy, L.Schillinger and A.Perveyrie

The calculation of the sequestered carbon dioxide inside a plant can be estimated with the following formula :

$$Sequestered\ CO_2 = \rho_0 \times \frac{1}{2} \times 3.67$$

Where:

- ½ is an estimation of the percentage of carbon in plants
- 3.67 allows the conversion from biogenic carbon to carbon dioxide.
- ρ_0 is the density of the plant at 0% of moisture content. It can be estimated with the following formula from the density at a moisture content $\omega < 25\%$:

$$\rho_0 = \rho_{\omega<25} \times \frac{100 + 0.45\ \omega}{100 + \omega}$$

In an LCA, the capacity of storage of carbon by vegetation can be taken into account in different ways. Many traditional LCA have employed static methods that do not consider the time variable.

- **Static LCA methods**

The 0/0 approach is based on the idea that the carbon absorption of a bio-based product is balanced by the equivalent carbon emission at its end of life. Hence in this case, no consideration of the biogenic carbon is made in the calculation of the LCA. A lot of traditional LCAs use this approach, as the existing standards do not provide consistent guidelines on the valuation of biogenic carbon storage. This method does not allow the characterisation of carbon storage. Hence, the lack of standards on this aspect does not encourage designers to choose bio-based materials.

The -1/+1 approach considers all the flows of carbon in the LCA. In stage A (raw materials supply), the absorption of carbon by the plant is considered as a negative Global Warming Potential (GWP). Then in stage C (end of life), the emission of biogenic carbon is considered as a positive GWP. The overall result is zero on the whole life cycle, but the flows of carbon are detailed in the model. It leads to different results when considering cradle-to-gate impact for example. This can lead to distorted interpretation of the impact of products when the absorption of carbon by the plant is considered but the emission at the end-of-life is hidden.

- **Dynamic LCA method**

To consider the delay of carbon release induced by the use of vegetal products, a dynamic approach to LCA can be implemented. One approach was proposed by Levasseur et al. in 2010 and takes into account the time of emission and time of absorption of CO2.

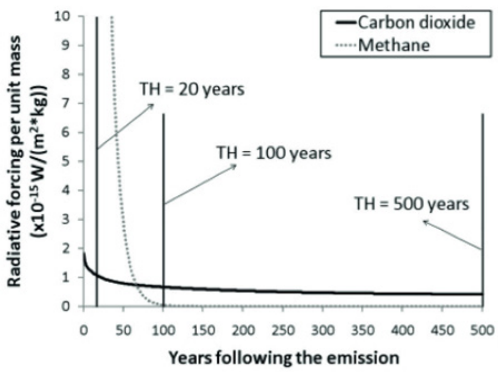


Fig. 10.9 - Radiative forcing of greenhouse gases

A first parameter to consider is radiative forcing. It measures the influence of a specific gas on climate change. A positive forcer is associated to a warming of the earth's surface. The radiative forcing of greenhouse gases decreases with the time following the emission. This is characterized by the dynamic characterization factor (DCF) calculated as :

$$DCF_{inst,GHG}(t-ti) = \int_{ti}^{t} a_{GHG} \times C_{GHG}(t)\, dt$$

Where a_{GHG} is the specific radiative forcing of the greenhouse gas per mass unit

And C_{GHG} is the decay model of a greenhouse gas pulse.

The DCF is then used in the calculation of the instantaneous Global Warming Impact (GWI) using the following equation:

$$GWI_{inst}(t-ti) = \sum_{GHG}\sum_{t} g_{GHG}(t) \times DCF_{inst,GHG}(t-ti)\ [W/m^2]$$

Where g_{GHG} is the mass in kg of the greenhouse gas

The cumulative impact at an instant t is calculated as the sum of the instantaneous GWI until instant t.

$$GWI_{cum}(t) = \sum_{j=0}^{t} GWI_{inst,GHG}(t-tj)\ [W/m^2]$$

Then the dynamic Global Warming Potential is expressed as such :

$$GWP(t) = \frac{GWI_{cum}(t)}{DCF_{inst,CO2}(t)}\ [kgCO_2eq]$$

This complete and more accurate type of analysis can take into account the effects of delayed emissions. It is however hard to implement and simplified methods have been developed on this basis.[6]

- **Simplified dynamic method**

There is not yet consensus in the standards regarding the consideration of biogenic CO_2 in LCA. Using dynamic LCA the equation of GWP for products including biomass is :

$GWP_{100} - GWP_{bio} = GWP_{net}$

One method was developed by Guest in 2013 in which simplified cofficients are employed. This the method we chose to implement in our study to valorise the carbon storage effect.

The GWP_{bio} factors depend on rotation period and storage period. They are found in Tab.10.1. To calculate the GWP_{bio}, the formula becomes :

GWP_{bio} = Sequestered CO_2 x $GWP_{bio\ factor}$

[7]

Rotation period (years)	Storage period in the anthroposphere (years)										
	0	10	20	30	40	50	60	70	80	90	100
1	0.00	−0.07	−0.15	−0.23	−0.32	−0.40	−0.50	−0.60	−0.71	−0.84	−0.99
10	0.04	−0.04	−0.12	−0.20	−0.28	−0.37	−0.46	−0.57	−0.68	−0.80	−0.96
20	0.08	0.00	−0.08	−0.16	−0.24	−0.33	−0.42	−0.53	−0.64	−0.76	−0.92
30	0.12	0.04	−0.04	−0.12	−0.20	−0.29	−0.38	−0.48	−0.60	−0.72	−0.88
40	0.16	0.09	0.01	−0.08	−0.16	−0.25	−0.34	−0.44	−0.55	−0.68	−0.84
50	0.20	0.13	0.05	−0.03	−0.12	−0.21	−0.30	−0.40	−0.51	−0.64	−0.80
60	0.25	0.17	0.09	0.01	−0.07	−0.16	−0.26	−0.36	−0.47	−0.59	−0.75
70	0.29	0.22	0.14	0.06	−0.03	−0.12	−0.21	−0.31	−0.42	−0.55	−0.71
80	0.34	0.26	0.18	0.10	0.02	−0.07	−0.17	−0.27	−0.38	−0.50	−0.66
90	0.38	0.31	0.23	0.15	0.06	−0.03	−0.12	−0.22	−0.33	−0.46	−0.62
100	0.44	0.37	0.29	0.21	0.12	0.032	−0.06	−0.16	−0.27	−0.4	−0.56

Tab.10.1 - GWP_{bio} factor based on storage and rotation period @Guest, Cherubini and Stromann

- **Calculation of the GWP_{bio} for our project**

We used the Guest method to calculate the GWP_{bio} of our three types of biomass: straw, samba wood and bamboo. The calculations are summarized in the tables Tab. 10.2, 10.3 and 10.4.

As expected, for an equivalent mass, the species growing faster have a better capacity of carbon storage. However, when considering the GWP_{bio} per volume, the results change a little due to the different species density. The straw has the lower density and therefore, the lowest GWP_{bio} /m^3. Bamboo grows rather fast with a rotation period estimate of 5 years and it is quite dense making it the best carbon storage option out of the three calculated.

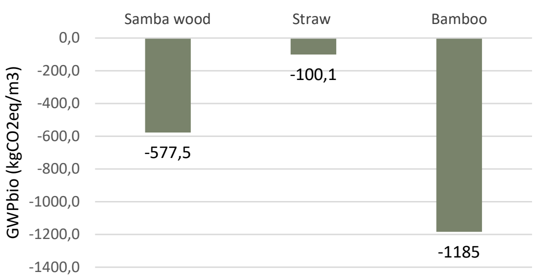


Fig. 10.10 - Comparison of GWP_{bio}/kg

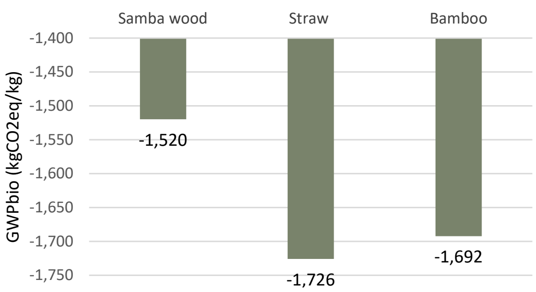


Fig. 10.11 - Comparison of GWP_{bio}/m^3

Wood density	380	kg/m^3
Moisture content	12	%
Wood density 0%	357,6	kg/m^3
Sequestered CO_2	656,2	kg/m^3
Rotation period	30	years
GWPbio factor	-0,88	
GWPbio	-577,5	kgCO_2eq/m^3
GWPbio	-1,520	kgCO_2eq/kg

Tab. 10.2 - Calculation of GWP_{bio} for samba wood

Straw density	58	kg/m^3
Moisture content	10	%
Density 0%	55,1	kg/m^3
Sequestered CO2	101,1	kg/m^3
Rotation period	1	year
GWPbio factor	-0,99	
GWPbio	-100,1	kgCO_2eq/m^3
GWPbio	-1,726	kgCO_2eq/kg

Tab. 10.3 - Calculation of GWP_{bio} for straw

Bamboo density	700	kg/m^3
Moisture content	12	%
Wood density 0%	658,8	kg/m^3
Sequestered CO2	1208,8	kg/m^3
Rotation period	4	years
GWPbio factor	-0,98	
GWPbio	-1185	kgCO_2eq/m^3
GWPbio	-1,692	kgCO_2eq/kg

Tab. 10.4 - Calculation of GWP_{bio} for bamboo

2. LCA of bio-bricks

2.a. Goal and scope definition

- **Goal definition**

The goal of the LCA study is to assess the environmental impact of the different compressed earth bricks produced and tested throughout this thesis project. The aim is to be able to compare the environmental impact of bricks containing different amounts and types of vegetal fibers to motivate the choice of one specific product for this project.

The study shall also be used to compare the environmental impact of this structural material with those of other loadbearing solutions for education means. The study includes a comparative assertion and is planned to be disclosed to the public.

Finally, the LCA will also be producing a complete product assessment to be used in a building life cycle assessment specific to the local construction in Senegal.

- **Scope definition**

The functional unit will be 1 m^3 of loadbearing 30-cm thick wall made of compressed earth blocks and loam mortar serving 100 years in construction.

The study will be conducted from cradle to grave (A to D) for the impact assessment to serve in the context of the construction of the building in Senegal. The focus will be put on raw materials supply (A1), production (A3) and construction process (A5) for the comparison between different bricks and with other loadbearing materials. The unit processes considered for each life cycle stage are listed in Tab. 10.5.

The study will focus on the Global Warming Potential expressed in kgCO_2eq. The allocation cut-off will be implemented for reused materials according to the EN15804. The data will be extracted from the ecoinvent database 3.4.

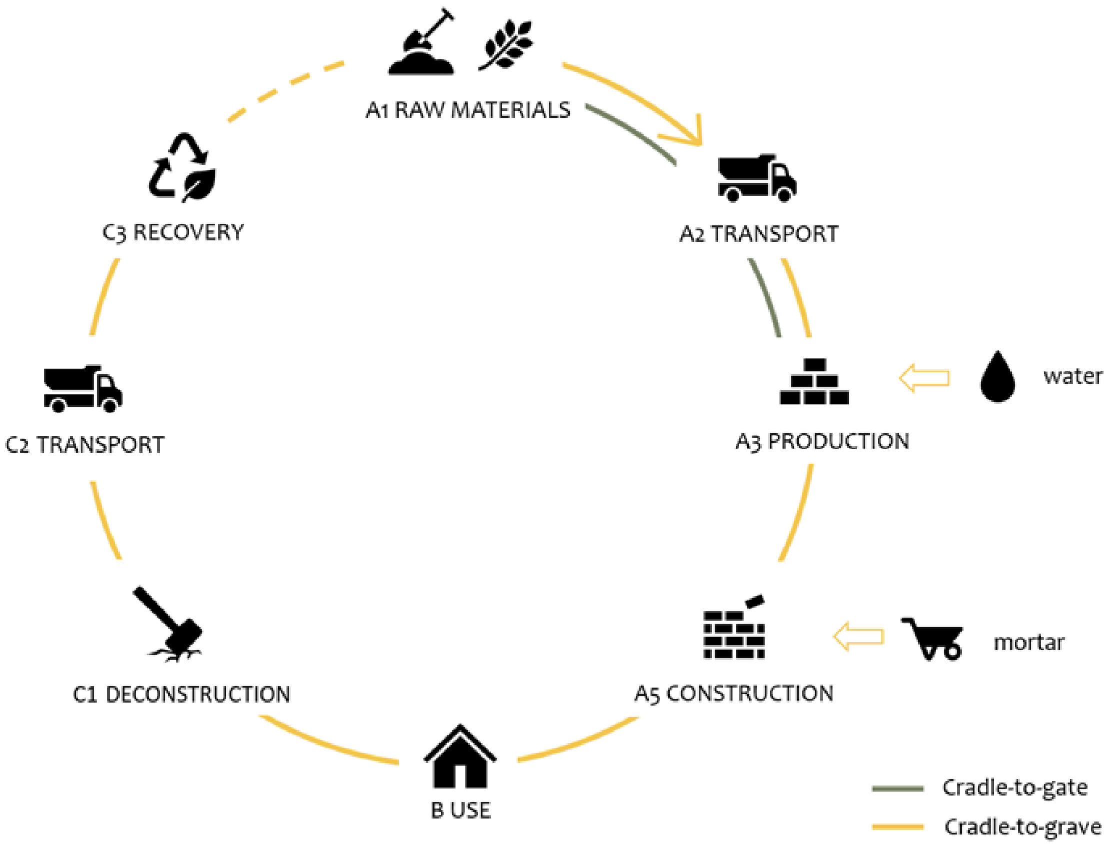


Fig. 10.12 - Life cycle of the compressed earth block wall

A. Production & construction	B1. Use / C. End of life	D. Benefits
A1. Raw materials: Earth, gravel, vegetal fibers	B1. Use	D. Benefits: Biogenic carbon
A2. Transport to production site: 10 km with small truck	C1. Deconstruction: Diesel for jackhammer	
A3. Production: Water	C2. Transport: 10 km with small truck	
A4. Transport to building site: No transport	C3. Recovery	
A5. Construction process: Mortar	C4. Disposal: Inert waste, biowaste	

Tab. 10.5 - Unit processes considered for each life cycle stage

2.b. Inventory analysis

The unit processes considered for each life cycle stage are listed in Tab. 10.5. The stages in yellow are the ones taken into account in the comparison with more traditional structural elements. The whole life cycle is considered in the building projects' LCA. The listing of processes was inspired by two Environmental Product Declarations (EPD) for compressed earth bricks from the Inies database. [9] [10]

The first step of the inventory quantifies each unit process. The 1 m² section of 30 cm-thick wall contains 62 bricks and 1,5 cm of mortar in between the bricks. The composition of the bricks and the mortar are summarized in Tab. 10.6 in percentage of the total volume.

For the bamboo, , the impact comes from an EPD by MOSO for bamboo products, where only the part concerning the cultivation of bamboo was considered.

We consider that the soil is coming directly from the excavation on site. Therefore, it comes with zero transport while the sand and gravel must be transported from an exploitation site near the river. The estimated transportation is 10 km in a small truck (3,5 - 7 t).

The deconstruction is considered to be made mostly with non-powered tools; we took into account the use of a pneumatic hammer, power 1850 W, consuming diesel and being used 5 min for each square meter of wall.

We consider that after deconstruction, the organic waste is transported to be composted naturally in open air disposal. The estimated transportation is 10 km in a small truck (3,5 - 7 t). The disposed vegetal fibres will emit greenhouse gases into the air during the recovery process and are therefore considered as biowaste. The rest of the materials, earth, sand and gravel, are considered inert materials. All the datasets used in the LCA are listed in the Tab. 10.7.

Straw bio-brick		Bamboo bio-brick		Wood bio-brick		Mortar	
Earth	66%	Earth	73%	Earth	72%	Sand	40%
Water	13%	Water	15%	Water	14%	Earth	30%
Gravel	10%	Gravel	11%	Gravel	11%	Water	40%
Straw	10%	Bamboo	2%	Wood	3%		

Tab. 10.6 - Composition in % of the total volume of bio-bricks and mortar

Type	Name	FU	Source	Country
Transformation	Clay soil, compacted dry density, 1600 kg/m^3	m^3	One Click LCA	Senegal
Transformation	Gravel, round | gravel and sand quarry operation	kg	ecoinvent	RoW
Transformation	Sand | gravel and quarry operation	kg	ecoinvent	RoW
Transformation	Straw | wheat production	kg	ecoinvent	RoW
Transformation	Wood chips, wet, measured as dry mass | wood chips production, hardwood, at sawmill	kg	ecoinvent	RoW
Transformation	Bamboo production	kg	EPD Moso	China
Transformation	Transport, freight, lorry 3.5 - 7.5 metric ton, EURO3	tkm	ecoinvent	RoW
Transformation	Tap water| tap water production, underground water without treatment	kg	ecoinvent	RoW
Transformation	Diesel, burned in building machine| processing	MJ	ecoinvent	Global
Transformation	Biowaste| treatment of biowaste, industrial composting	kg	ecoinvent	RoW
Inert material landfill	Inert waste, for final disposal| treatment of inert waste, inert material landfill	kg	ecoinvent	RoW

Tab 10.7 – Datasets and data sources used in the LCA of biobricks

2.c. Impact assessment

During the impact assessment we allocate the biogenic GWP in stage D to vizualize better its impact. The results obtained for each phase and each bio-brick are listed in Tab. 10.8. and plotted in Fig. 10.13.

We can already see that the most polluting stages are the supply of raw materials and the end-of-life especially, because of transportation of important volumes of earth. All those environmental impacts are fairly low as a small portion of vegetal fibres is enough to compesate it. Indeed, regarding the environmental impact, vegetal fibre as a consequent GWP_{bio}.

Stages	Straw bio-brick	Wood bio-brick	Bamboo bio-brick
A1	1,31E+00	1,34E+00	1,65E+00
A2	3,92E-01	3,92E-01	3,92E-01
A3	1,40E-02	1,40E-02	1,40E-02
A1-A3	1,71E+00	1,75E+00	2,06E+00
A5	4,01E-01	4,01E-01	4,01E-01
B	0,00E+00	0,00E+00	0,00E+00
C1	6,15E-02	6,15E-02	6,15E-02
C2	2,41E+00	2,41E+00	2,42E+00
C4	2,11E-01	1,67E-01	3,53E-01
D	-2,77E+00	-1,95E+00	-4,34E+00
Cradle-To-Gate	-1,06E+00	-2,03E-01	-2,29E+00
Cradle-To-Grave	2,03E+00	2,84E+00	9,46E-01

Tab 10.8 – Results of the LCA of the bio-bricks

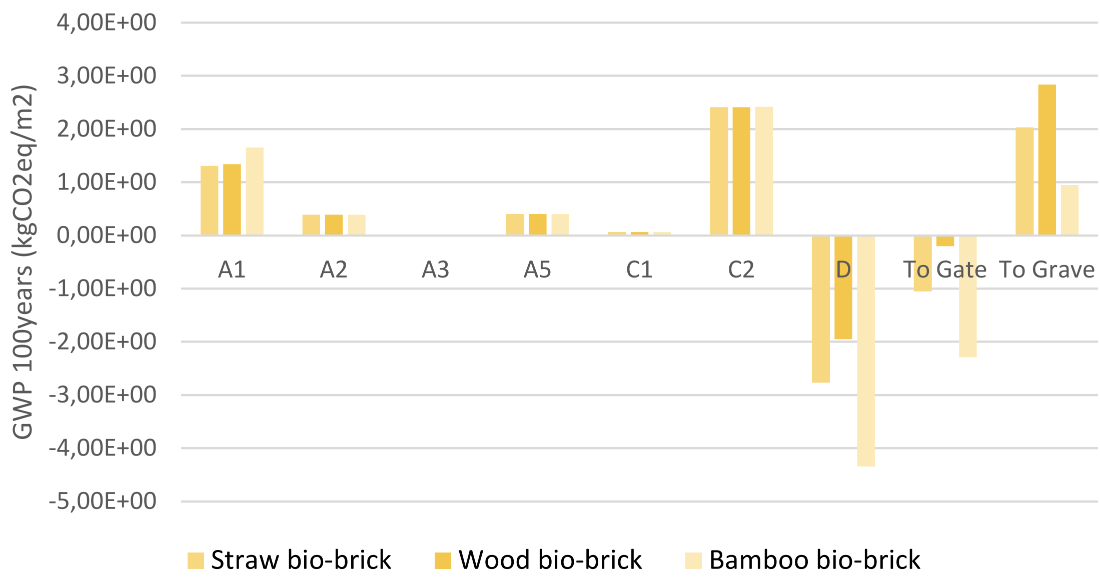


Fig 10.13 – GWP of the bio-bricks by phases ($kgCO_2eq/m^2$)

2.d. Interpretation

- **Comparison between vegetal fibres**

When comparing between the different bio-bricks on the cradle-to-gate impact, we can see that fibres production and biogenic carbon are the two varying parameters. Straw has a very low production impact, and an important biogenic carbon negative impact. Wood has a more important production impact but its GWP_{bio} is much lower, making the total cradle-to-gate impact more important. Bamboo has an important fiber production impact but an even more important GWP_{bio} giving it the lowest cradle-to-gate potential impact.

Straw had the most important GWP_{bio} per kilogram closely followed by bamboo. However, the mass of bamboo fibres used in the bricks is almost twice the mass of straw explaining the lower overall impact of the bamboo bio-brick.

We can see in the literature that the impact of our bio-bricks is about ten times inferior to most Compressed Earth bricks (CEB) considering A1 - A3. This is due to the supply of earth on site, and the use of manual techniques with no electricity or fuel. [11]

Putting in perspective the environmental impact and the compressive strength found in part IX, we can see that the bamboo bio-brick is the one having the lowest GWP and the highest mean compressive strength. The straw bio-brick has the second-best compressive strength and GWP.

For the choice of material, the bamboo fibres would therefore be preferred. Depending on local availability, we can still state that straw remains a good option. As vegetal fibres can vary a lot in sizes, shapes and density, even for the same material, it is therefore recommended to test the specific available fibres before using them on site to get the best results as possible.

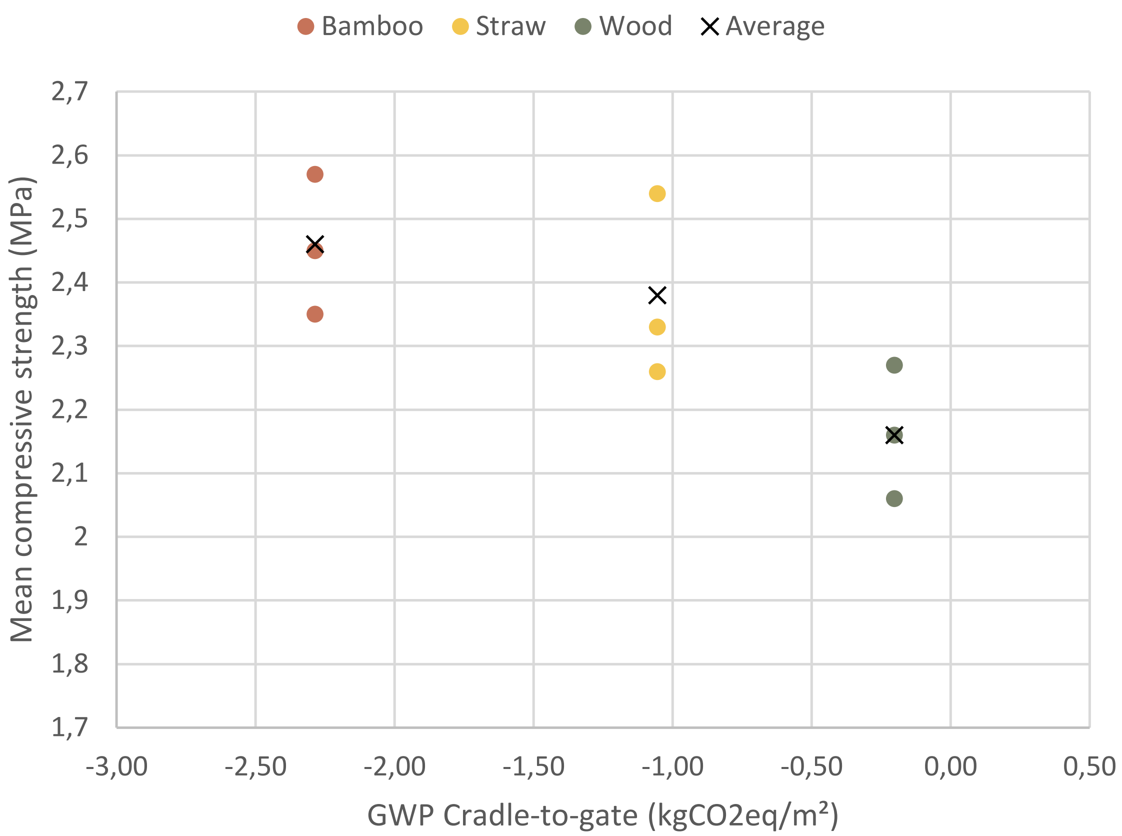


Fig. 10.14 - Comparison between bio-bricks on GWP and compressive strength

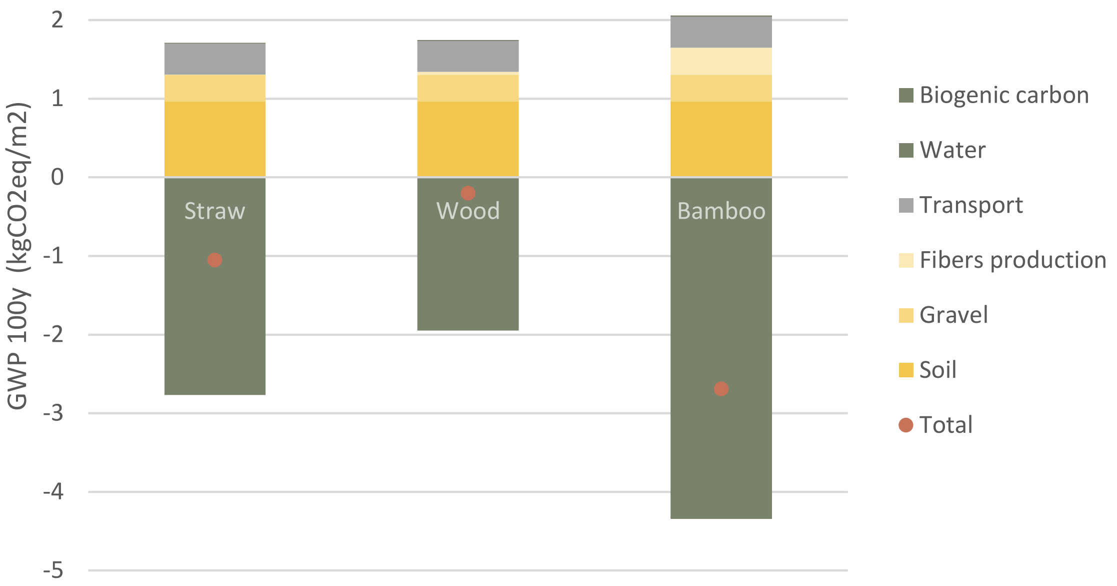


Fig. 10.15 - Comparison cradle-to-gate impact between bio-bricks

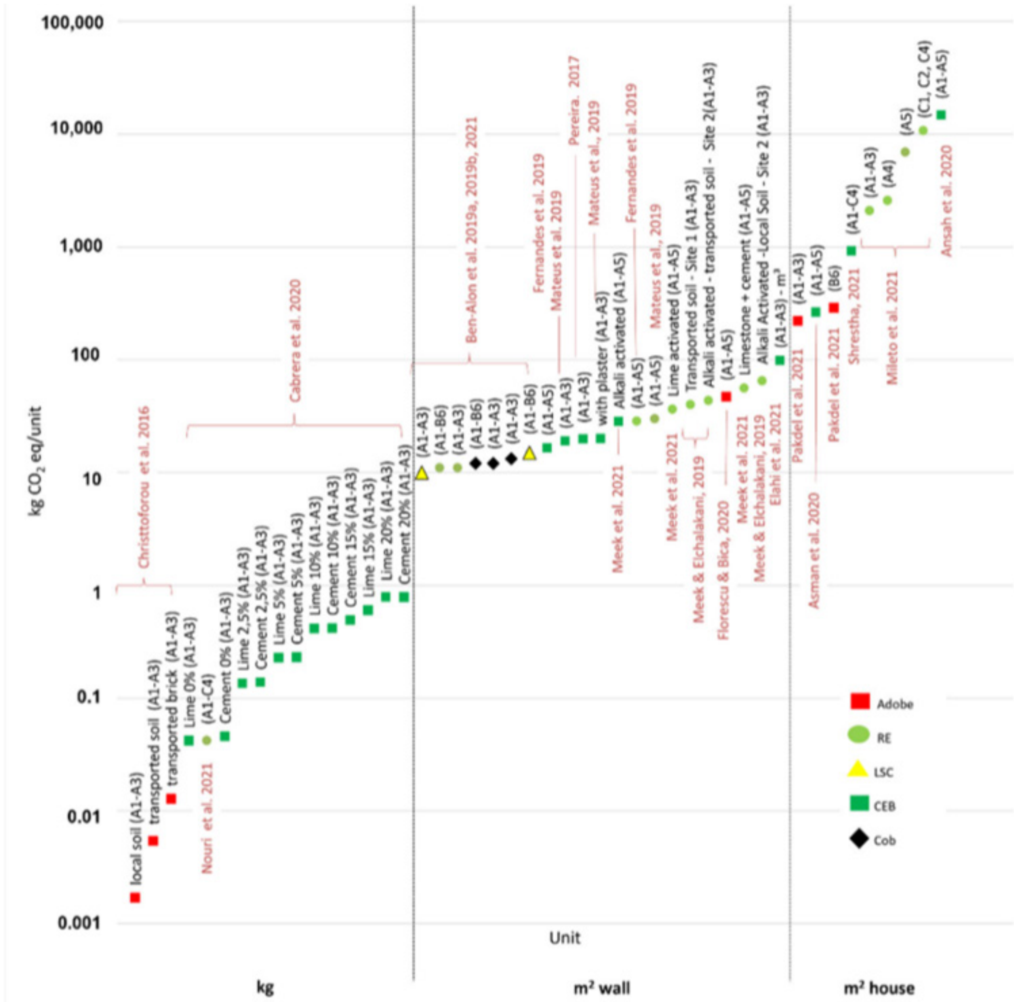


Fig. 10.16 - Literature review of LCA of earth materials. @Arduin et al.

- **Comparison with other structural materials**

The bio-bricks are also compared to other structural solutions for the same functional unit of 1 m^2 of loadbearing wall. For the comparison, the thickness of each wall was chosen to have the same compressive strength as our bamboo brick wall, that is to say 2.46 MPa. In cases where this thickness is inferior to the minimum recommended thickness for the structural material studied, the minimum thickness was considered.

We therefore see that the for the cradle-to-gate impact, the bio-bricks appear way more environmentally friendly for the same structural capacities than other traditional construction materials. The bio-bricks all have a negative cradle-to-gate impact and could be compared to X-LAM. In rural Senegal, it appears as one of the most ecofriendly options for constructing buildings, especially in comparison to the concrete blocks that are being employed more and more in these regions.

However, it should be noted that the bio-bricks have a limited structural capacity and cannot be used in buildings with more than 2 levels. Moreover, depending on the region the availability of materials can also play a decisive role in design choices as the impact of transport was not considered in this comparison.

- **Limits**

The limits of the study are found in the lack of local data, forcing the use of Rest of the World data or data corrected by algorithms, which are less precise than real local data. In some cases, the data was taken from other parts of the world, and this could also explain some error in the results. The distances and modes of transport estimation could also be a source of imprecision.

The composition of the bricks was tested in part IX but the soil used is not the same as Senegalese soil, and the composition on site could vary. The fibres used in experimentations may also be different than the local vegetal fibres found in Senegal. The mortar composition was taken from literature and could also need to be adapted to the local composition of the soil.

The end of life was chosen as the worst option, landfill, but the earth could be reused in building or agricultural projects.

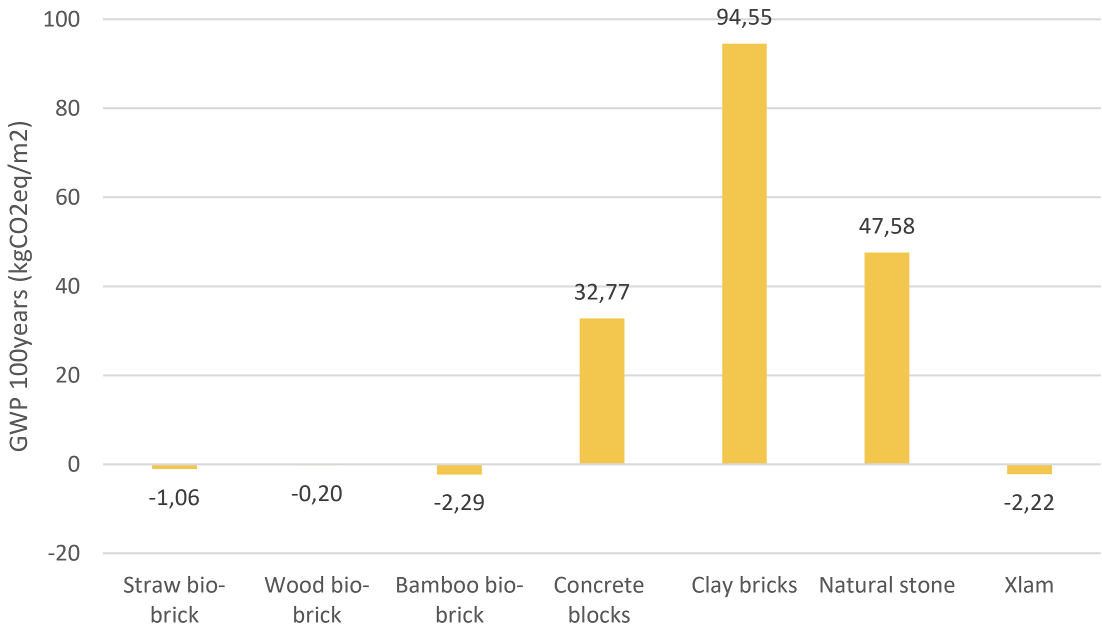


Fig. 10.17 - Comparison with other structural materials

3. LCA of the projected building

3.a. Goal and scope definition

- **Goal definition**

The goal of the LCA study is to assess the environmental impact of the school building project in Baghere, Senegal. The aim is to be able to understand which part of the projects are the most damaging to the climate. The study will also be used to compare this raw earth building project to other school buildings, and environmental objectives.

- **Scope definition**

The functional unit will be the whole school consisting in 6 compressed earth blocks buildings for a total indoor area of 482 m² maintained for 100 years.

The study will be conducted from cradle to grave (A to D). The biogenic carbon impact potential will be considered in category D for easier visualization.

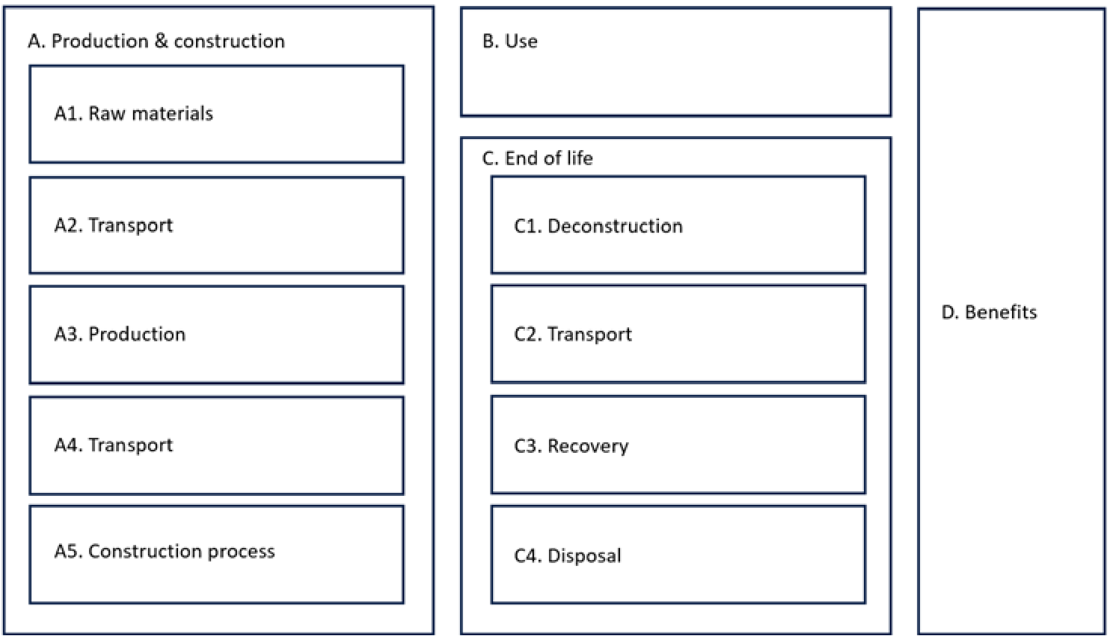
The study will focus on the IPCC Global Warming Potential expressed in kgCO_2eq. The allocation cut-off will be implemented for reused materials according to the EN15804. The data will be extracted from the ecoinvent database 3.4 and other databases available on OneClick LCA.

3.b. Inventory analysis

The stages of the building life cycle were implemented according to the European Normative EN 15804.

The first step of the inventory is quantifying each unit process. First the unit processes of each material were computed. Then for each type of partition, the quantity of each material was assigned. Finally for each building, the surface of each partition was computed, as well as the number of windows and doors, the number of structural elements and rainwater pipes.

For the inventory, some products were the object of a prior LCA to define their potential impact before being used in the calculation. That is the case with bio-bricks, as described in the last chapter. The same kind of analysis was conducted for the straw-lightweight loam. Several EPDs were also computed to create the functional units of the windows and doors.



Tab. 10.9 - Stages of building lifecycle according to EN 15804

The transport of each material was considered to be carried out in a small truck (3.5 - 7 t). The distance was chosen based on documentation from Balouo Salo on local availability of materials in Baghere, Senegal as described in Tab. 10.10.

No engines or power tools are considered in the LCA except for the use of diesel-powered pneumatic hammers for the deconstruction of the walls and foundations.

The end of life of all products was considered as dumping in a landfill, considering the worst-case scenario. The transport to the landfill was considered with a distance of 10 km. The GWP impact was taken from the ecoinvent database and differs based on the material.

Availability	Distance considered
Locally	10 km
Regionally	100 km
Nationally	500 km

Tab. 10.10 - Transport distance considered based on availability

All the datasets used, and their sources are listed in Tab. 10.11. The data was taken either for Senegal using the OneClick LCA computed data or for the rest of the world when available. When appropriate data were not available for the region considered, some data from other countries was used. The geographical relevance of the data is specified in the following tables.

Type	Name	FU	Source	Country
EPD	Galvanized die rolling steel, corrugated and rectangular, 7850 kg/m^3	kg	Ternium Mexico	Mexico
EPD	Natural clay lime plaster, Clime	kg	Armourcoat	United Kingdom
Calculated dataset	Rammed earth wall, cement stabilised, 300 mm, 549 kg/m^2, 1830 kg/m^3	m3	One Click LCA	Senegal
Calculated dataset	Softwood board, kiln dried, sawn, 440 kg/m^3, 10% moisture content, coniferous wood	m3	One Click LCA	Senegal
Calculated dataset	Softwood lath (stud), kiln dried, planed, 440 kg/m^3, 10% moisture content, coniferous wood	m3	One Click LCA	Senegal
Calculated dataset	Softwood beam, kiln dried, planed, 440 kg/m^3, 10% moisture content, coniferous wood Senegal	m3	One Click LCA	Senegal
Calculated dataset	External wood door, 2,1 x 1 m	unit	One Click LCA	Senegal
EPD	Hinges and fasteners for door and window shutters, European average	unit	ARGE	Europe

Tab. 10.11 - Datasets used in the LCA of the building project - 1

Type	Name	FU	Source	Country
Calculated dataset	Extruded aluminium profiles for window and door frames, generic, 50% recycled content	kg	One Click LCA	Senegal
Calculated dataset	Polypropylene (PP) pipe for drainage and sewerage networks, DN 150 mm (6 in)	m	One Click LCA	Senegal
Calculated dataset	Galvanized steel pipes, DN 150 mm, (5 in), 22.29 kg/m, wall thickness: 4.50 mm	m	One Click LCA	Senegal
EPD	Steel gutters, semicircular, 1.5 kg/m, Gouttière demi-ronde en acier [333 mm]	m	INIES	France
Study LCA	Impact Total per Life Cycle Phase for a Woven cotton Pant	kg	the cotton foundation	World
Calculated dataset	Quarry stone, 1800 kg/m^3	m3	One Click LCA	Senegal
Calculated dataset	Masonry mortar, silica sand based	kg	One Click LCA	Senegal
EPD	Steel profiles, 7850 kg/m3	kg	Associación Sostenibilidad Siderúrgica	Spain
Transformation	Biowaste {RoW}| treatment of biowaste, industrial composting	kg	ecoinvent	RoW
Inert material landfill	Inert waste, for final disposal {RoW}| treatment of inert waste, inert material landfill	kg	ecoinvent	RoW

Tab. 10.12 - Datasets used in the LCA of the building project - 2

3.c. Impact assessment

During the impact assessment we allocated the biogenic GWP in stage D to better visualize its impact. The results obtained for each phase are plotted in Fig. 10.18.

We can already see that the most impacting stage is the supply of raw materials. We also see that the biogenic carbon impact potential is important. It is explained by the use of straw in large quantities in lightweight loam, and the wooden structures, windows and doors employed in the project. The overall potential impact of the project is of 36,5 $kgCO_2eq/m^2$.

3.d. Interpretation

- **Comparison between elements**

The total GWP impact can also be plotted in categories. We grouped together all the outdoor spaces elements (floors, stairs and canopies, all the structural elements (stone foundations, wood and metal beams), the plumbing systems (metal and plastic pipes), windows and doors (wood and metallic fasteners) and all the partitions (Roof, ceilings, floors and walls, excluding punctual structural elements).

Outdoor spaces, windows and doors have a negative greenhouse gas impact due to the important number of wooden elements in those categories. Plumbing has the worst overall impact. It contributes up to 52% in the impact of the project. Moreover, the structural category's impact is driven mostly by the stone foundations.

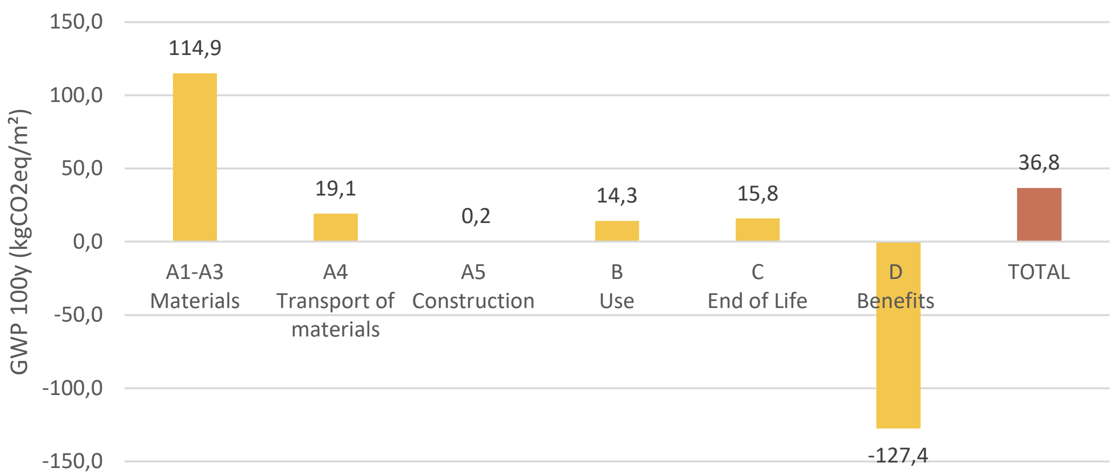


Fig. 10.18 - GWP of the project by phases

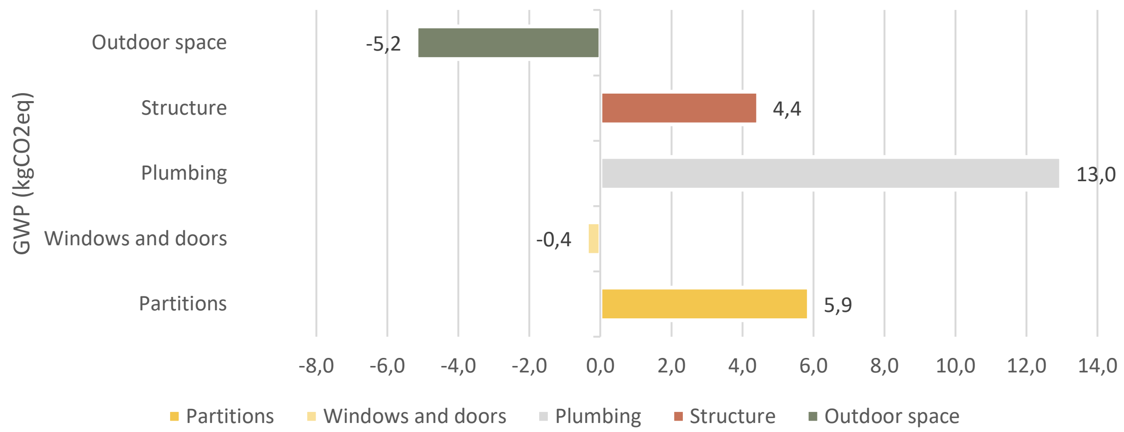


Fig. 10.19 - GWP of the project by categories

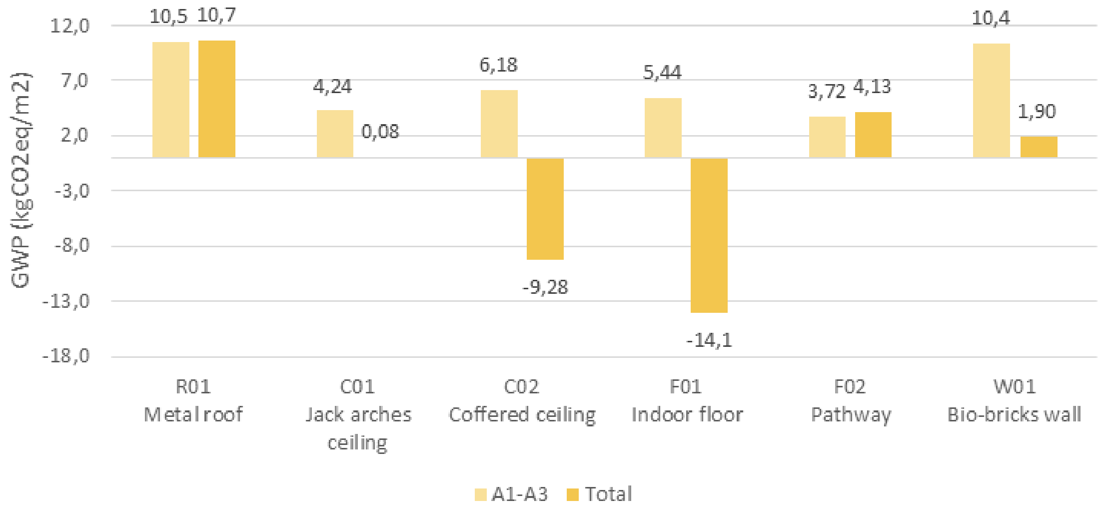


Fig. 10.20 - Comparison between the GWP of different partitions

The different partitions have been compared by square meter in Fig. 10.18. Two of them have negative impacts : coffered ceiling and indoor floor. They are the ones using most clay-straw lightweight loam, along with wooden supports. The jack arches ceiling has an impact close to zero, and the bio-bricks walls also have a small impact. The partition with greatest impact is the metal roof, which is only made of corrugated iron sheets.

The buildings contribute in different ways to the potential impact of the school. The classrooms make up for 39% of the GWP, which is also explained by the higher surface of the six modules. Then the common parts impacts are the greatest. They contain the underground pipes collecting rainwater, the entrance canopies and the stabilized earth pathways

The laboratory has the lowest impact per square meters of all the buildings and this is due to the important number of canopies and windows which both have a negative GWP, and a small number of doors, compared to the cafeteria or the classrooms' buildings.

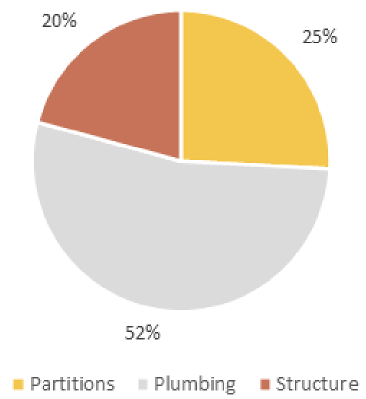


Fig. 10.21 - Part of GWP by category

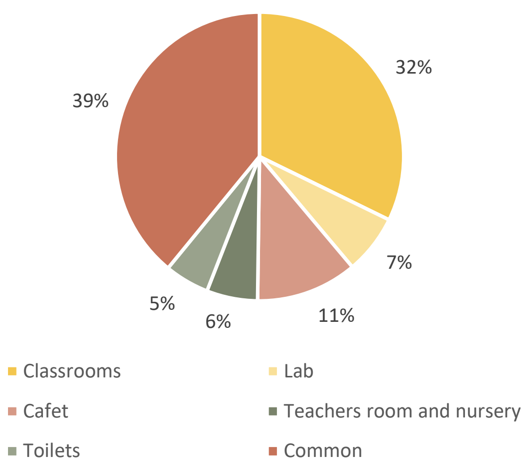


Fig. 10.22 - Part of GWP by building

- **Comparison with benchmark and label objectives**

Eventually, we decided to compare the overall GWP impact of our building project to the Carbon Heroes benchmark comparing 132 schools over the world. The mean GWP for schools globally according to this benchmark is 451 $kgCO_2eq/m^2$. Our project is 10 times less impacting than the mean school building built globally. [13]

We also see that our project is compliant with the maximum emissions of the building construction imposed by 2000-W Society, which is 8,5 $kgCO_2eq/m^2$.year. [14]

The project could also obtain the best carbon level C2 for the French ecolabel Energie-Carbone E+C-, where the maximum for the level C2 for this type of building is of 750 $kgCO_2eq/m^2$. [15]

The construction of buildings with raw earth materials seems very low-emission. However this study is context-specific and the results cannot be used as an ultimate conclusion.

- **Limits**

Much like the LCA of the bio-bricks, the limits of the study are found in the lack of local data, leading us to use either 'Rest of the World' categorised data or data corrected by algorithms, which are less accurate than real local data. The data was sometimes even taken from other parts of the world, and this could also induce some error in the results. The distances and modes of transport estimation could also be a source of imprecision. They are in any case a reductive parameter to the applications of this LCA study which is quite specific to this case in point.

Besides, some impacts were not calculated, such as the furniture of the classes. No engine or power tools were imagined except for pneumatic hammers for deconstruction.

Finally, the study is limited to the Global Warming Potential when the construction could have other impacts on the environnment, on land use and water depletion for example.

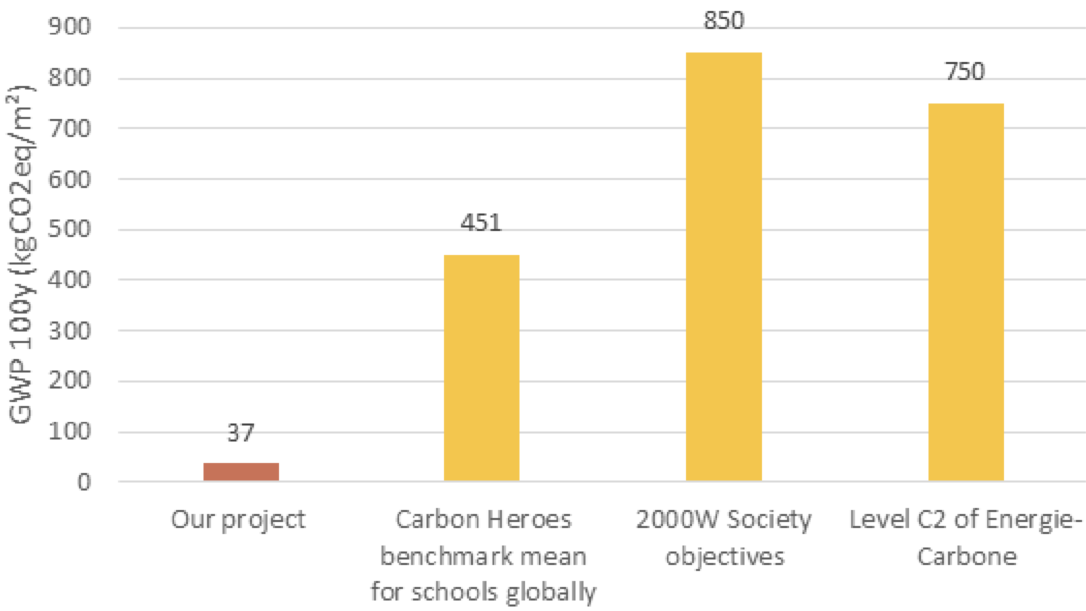


Fig. 10.23 - GWP of the project by categories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CONCLUSION

The design of the school of Baghere as our thesis project has been a stimulating challenge. The aim was to create a sustainable building that could address the issue of education in Senegal. Indeed, our first ambition for the thesis was to explore the concept of sustainable design. Our vision of sustainability consisted of using natural materials and simple construction techniques adapted to the context, following the low-tech principle. We indeed believe that over-complexification is not the solution to the environmental crisis. Using raw earth as a resilient construction material can be a sensible alternative to polluting materials and processes commonly used in the building sector. Having chosen to focus on this material, we searched for a suitable architectural project and discovered the Kaira Looro Competition. Every year, it offers a design opportunity in the rural regions of Senegal. The 2023 subject was a primary school in Casamance which gave us the opportunity to learn more about school architecture and different concepts around education that have been developed in Africa and elsewhere.

One of the most interesting and challenging aspects of our thesis work derived from the context. The 2023 Kaira Looro competition made us discover Senegal and particularly the Casamance region. Helped by Raoul Vecchio from Balouo Salo, we were able to get an insight into the local ways of living, working, studying, and inhabiting. Those differences clearly had an influence on our design directions. The study of vernacular architecture was particularly inspiring. The solutions employed with minimal resources are ingenious and show a true knowledge of one's surroundings. Used for thousands of years, these vernacular techniques are still implemented in most of the constructions and have volved over time to suit the requirements of modern building. Furthermore, the traditional architecture also illustrates the local customs and the village organisation. We also studied the challenges faced by the local populations, in terms of education, but also other social and environmental problematics. Even though these multifactorial crises can never be solved by one building design, we tried to address them in our modest architectural proposition.

The Kaira Looro competition taught us how to design with constraints, but it also stimulated our curiosity and creativity by sharing a great diversity of architecture projects around the world designed with the same objective. Designing for an area and people far from us was a stimulating challenge. Indeed, not only did we want to draw inspiration from traditional architecture but also we had to take into consideration the preferences of the population that tends to admire modern architecture. Our proposition aims to find a compromise between a modern aesthetic and traditional building techniques. We had a lot of ambition for the project and put a lot of thought into implementing the different functions envisioned in a cohesive way. More than a school capable of meeting the challenges of education in Senegal, the building also intended to become a central gathering place for the village. The project offers spaces for different publics, from secret rooms destined for children to

an auditorium open to the whole community of Baghere and tends to encourage connections across ages and differences. Much like the villages of Casamance, the result is an ever-evolving agglomeration of interconnected spaces.

The construction process also presented its challenges, having to be carried out by the local community with little to no power tools. We decided to employ locally available materials as much as possible. We also considered the lack of electricity and opted for manually compressed earth bricks. Moreover, the building needed to offer a good indoor environment for teaching all year round despite the harsh tropical climate. With no reliable source of energy available, passive solutions were implemented to reduce heat and humidity as well as to control daylight. Natural ventilation, thermal mass, double roof, surrounding vegetation, louvres, and wall perforations were all made part of the project for this purpose.

A significant part of our thesis was dedicated to the study of raw earth as a building material. We had the opportunity to learn about its properties and applications. For this project, we chose to focus on compressed earth blocks and studied the stabilisation by different vegetal fibres: straw, wood and bamboo. We carried out experiments in the laboratory, making bricks and samples with manual presses. All compressive strength results were over 2 MPa, characterizing a usable load-bearing material. These results encourage the use of vegetal fibres in compressed earth blocks and bamboo fibres seem especially promising. However, we observed significant variations from on sample to another, and the number of tests was low, therefore these conclusions cannot lead to greater generalisation.

From the environmental point of view, the Life cycle Assessment of the produced bio-bricks showed a reduced global warming impact due to the local availability of the earth, its compostable nature and the use of vegetal fibres storing biogenic carbon. For the same compressive strength, the carbon footprint of raw earth bio-bricks was significantly lower than other structural materials like concrete or clay bricks. Once again, the use of bamboo fibres was found particularly beneficial. The Life Cycle Assessment of the building project also revealed a really low impact of the whole construction. The project is therefore an example of a low-carbon building.

LE VILLAGE is a suggestion for a school that embraces its environment and creates new possibilities. It offers spaces designed for different people and uses while leaving room for flexibility and evolution. It is also an example of a low-tech construction, minimising environmental impact and using resourceful solutions to adapt to its environment. The use of compressed raw-earth bio-bricks seems particularly advantageous for low-carbon buildings, and can offer interesting physical capacities for small building projects. The addition of vegetal fibres such as bamboo or wood can also enhance these properties while further reducing the environmental impact of the material.

BACKMATTER

REFERENCES

I. CONTEXT ANALYSIS

[1] Agence Nationale de la Statistique de la Démographie, 'LE SENEGAL EN BREF'. Accessed: Sep. 05, 2023. [Online]. Available: https://www.ansd.sn

[2] O. Fadiaba, S. Ndao, S. Seck, M. Signate, and J. Guitton, 'Sénégal', in Atlas des pêches et pêcheurs artisans d'Afrique de l'Ouest, IRD Éditions, 2021, pp. 131–136. doi: 10.4000/books.irdeditions.44091.

[3] Observatoire Vivre Ensemble, 'Dakar Senegal'. Accessed: Sep. 05, 2023. [Online]. Available: https://observatoirevivreensemble.org

[4] C. Camara, J. D. Hargreaves, and A. Clark, 'Senegal', Britannica Academic.

[5] Centre de suivi écologique (CSE), 'Annuaire sur l'environnement et les ressources naturelles du Sénégal', 2013.

[6] Bou El Mogdad, 'Geographie'. Accessed: Mar. 06, 2023. [Online]. Available: https://www.bouelmogdad.com

[7] L. White, C. C. Funk, J. Rowland, A. Adoum, G. Eiler, and J. Verdin, 'A climate trend analysis of Senegal', 2012. doi: 10.3133/fs20123123.

[8] Treccanni, 'Senegal Repubblica del ', Dizionario di Storia. Accessed: Apr. 23, 2023. [Online]. Available: https://www.treccani.it

[9] G. Hesseling, Histoire politique du Senegal, Karthala. 1985.

[10] The Heritage Foundation, 'SENEGAL', 2023.

[11] Ministère de l'Economie du Plan de la Coopération, 'Le Senegal en Bref - Investir au Senegal'. Accessed: Apr. 05, 2023. [Online]. Available: https://www.economie.gouv.sn

[12] des finances, et de la souveraineté industrielle et numérique, D. général du T. Ministère de l'économie, 'Situation économique et financière du Sénégal'. Accessed: Apr. 09, 2023. [Online]. Available: https://www.tresor.economie.gouv.fr

[13] The World Bank, 'GDP (current US$) - Senegal'. Accessed: Apr. 15, 2023. [Online]. Available: https://data.worldbank.org

[14] Agence Nationale de la Statistique et de la Démographie, 'Le Sénégal en chiffres - RGPHAE 2013', 2014.

[15] 'La Casamance : palmeraies, forêts et mangroves'. Accessed: Apr. 25, 2023. [Online]. Available: https://www.au-senegal.com

[16] B. Dieng, 'PLAN D'ACTION DE REINSTALLATION ABREGE (PARA) POUR LES TRAVAUX DE REHABILITATION DU TRONÇON SANDINIERI – TANAFF – FRONTIERE GUINEE', Aug. 2021.

[17] A. Seck, 'La moyenne Casamance. Etude de géographie physique', Rev Geogr Alp, vol. 43, no. 4, pp. 707–755, 1955, doi: 10.3406/rga.1955.1198.

[18] 'Le climat Sénégal'. Accessed: Mar. 05, 2023. [Online]. Available: https://www.donneesmondiales.com

[19] B. Diallo, LA CRISE CASAMANÇAISE Problématique et voies de solutions. L'Harmattan, 2009.

[20] 'Mandinka', Encyclopedia of World Cultures Supplement. 2023.

[21] M. F. Mbengue, C. T. Ndiaye, O. Sarr, E. Hadji, M. Gueye, and E. De Redaction, 'Rapport définitif RGPHAE 2013', Sep. 2014.

[22] Afrikemergence, 'La région de Sedhiou, première productrice de riz du Sénégal'. Accessed: Nov. 10, 2023. [Online]. Available: https://afrikemergence.com

[23] Service Régional de la Statistique et de la Démographie de Sédhiou, 'Situation économique et sociale - Région Sedhiou', 2019. [Online]. Available: www.ansd.sn

[24] Eiffage Senegal, ' La ville de Sedhiou change de visage'. Accessed: Nov. 10, 2023. [Online]. Available: https://www.eiffage.sn

[25] Commune de Baghère, 'Plan Local de Développement de la Communauté Rurale de Baghère', Feb. 2012.

[26] African Development Bank (AFDB), 'NATIONAL CLIMATE CHANGE PROFILE', 2018. Accessed: Jul. 25, 2023. [Online]. Available: https://www.afdb.org/en/documents/senegal-national-climate-change-profile

[27] W. Nguru et al., 'Spatial estimation of flood residual water cultivation (FRWC) potential for food security in Sédhiou and Tambacounda regions of Sénégal', Agric Water Manag, vol. 287, Sep. 2023, doi: 10.1016/j.agwat.2023.108445.

[28] 'Baghère : Sur les pas de la famille Aidara en Casamance', Senterritoires, 2021, Accessed: Feb. 23, 2023. [Online]. Available: http://senterritoires.com/baghere-sur-les-pas-de-la-famille-aidara-en-casamance/

[29] OMVG, 'Plan d'Actions de Réinstallation (PAR) Postes de transformation électrique au Sénégal', 2018.

[30] A. U. Kadiri and A. Kijko, 'Seismicity and seismic hazard assessment in West Africa', Journal of African Earth Sciences, vol. 183, Nov. 2021, doi: 10.1016/j.jafrearsci.2021.104305.

[31] O. Uduku, Learning Spaces in Africa. Routledge, 2018. doi: 10.4324/9781315576749.

[32] K. Majgaard and A. Mingat, 'Education in Sub-Saharan Africa - A comparative analysis', 2012.

[33] 'Senegal: Casamance - beating the odds to educate the children', The New Huminitarian, Dec. 2009.

[34] UNICEF, 'GirlForce - Skills, Education and Training for Girls Now', 2018.

[35] O. Uduku, 'Designing schools for quality: An international, case study-based review', Int J Educ Dev, vol. 44, pp. 56–64, Sep. 2015, doi: 10.1016/j.ijedudev.2015.05.005.

[36] UNICEF and Commission de l'Union Africaine, 'TRANSFORMER L'EDUCATION EN AFRIQUE - Résumé exécutif', 2021.

[37] B. A. Ryan and D. D. Mara, 'Ventilated Improved Pit Latrines', 1983.

[38] SDG4-Education 2030, 'CONTINENTAL EDUCATION STRATEGY FOR AFRICA 2016-2025', 2015.

II. VERNACULAR ARCHITECTURE

[1] G. Steyn and A. Roodt, "Two traditional African settlements-context and configuration."

[2] A. Galaup, "Les villages-centres du Sénégal," Cahiers d'outre-mer, vol. 44, no. 174, pp. 187–206, 1991, doi: 10.3406/caoum.1991.3390.

[3] A. Coly, "Organisation sociale, espace villageois et travail paysan au Sénégal Oriental. Exemple du village de Pathiab," 1999.

[4] I. Low, "Architecture in Africa: Situated modern and the production of locality," 2014. [Online]. Available: https://www.researchgate.net/publication/293222327

[5] J.-P. Bourdier and M. Trinh, Habiter un monde: Architectures de l'Afrique de l'Ouest. 2005.

[6] R. Anger and L. Fontaine, Bâtir en terre : du grain de sable à l'architecture. 2009.

III. BUILDING WITH EARTH

[1] A. M. Matos and H. Varum, "Self-Compacting Earth-Based Composites: Mixture Design and Multi-Performance Characterisation," Buildings, vol. 12, no. 5, p. 612, May 2022, doi: 10.3390/buildings12050612.

[2] H. Houben, Traité de construction en terre. 1989.

[3] UNESCO, "World Heritage List." Accessed: Mar. 14, 2023. [Online]. Available: https://whc.unesco.org

[4] R. Anger and L. Fontaine, Grains et batisseurs. La matière en grains, de la géologie à l'architecture , CRATerre Edition. Villefontaine, 2005.

[5] R. Anger and L. Fontaine, Batir en terre. Du grain de sable à l'architecture. Paris, 2009.

[6] Confédération suisse, Sols et constructions. 2015.

[7] G. Minke, Building with earth. 2006.

[8] AMACO, "Le feuillet d'argile ." Accessed: Mar. 14, 2023. [Online]. Available: https://amaco.org

[9] J. A. Calabria, W. L. Vasconcelos, and A. R. Boccaccini, "Microstructure and chemical degradation of adobe and clay bricks," Ceram Int, vol. 35, no. 2, pp. 665–671, Mar. 2009, doi: 10.1016/j.ceramint.2008.01.026.

[10] T. W. Lambe, "The Structure of Compacted Clays," Journal of the Soil Mechanics and Foundations Division, vol. 84, no. 2, May 1958, doi: 10.1061/JSFEAQ.0000114.

[11] P. Delage, M. Audiguier, Y.-J. Cui, and M. D. Howat, "Microstructure of a compacted silt," Canadian Geotechnical Journal, vol. 33, no. 1, pp. 150–158, Mar. 1996, doi: 10.1139/t96-030.

[12] T. Li Piani et al., "Dynamic behaviour of adobe bricks in compression: The role of fibres and water content at various loading rates," Constr Build Mater, vol. 230, p. 117038, Jan. 2020, doi: 10.1016/j.conbuildmat.2019.117038.

[13] E. Cadoni, K. Labibes, C. Albertini, M. Berra, and M. Giangrasso, "Strain-rate effect on the tensile

behaviour of concrete at different relative humidity levels," Mater Struct, vol. 34, no. 1, pp. 21–26, Jan. 2001, doi: 10.1007/BF02482196.

[14] C. Gnagne, "Riabilitazione del complesso Al-Nuri nella Città Vecchia di Mosul Scuola secondaria in terra cruda - Relazione," 2021.

[15] W. Carazas Aedo, "TEST CARAZAS Manual pedagógico," 2017.

[16] A. Kouka and J. Ouedraogo, "Stabilisation de matériaux de construction durables et écologiques à base de terre crue par des liants organiques et/ou minéraux à faibles impacts environnementaux," Université Paul Sabatier - Toulouse III, 2020.

[17] J. Paulus, "CONSTRUCTION EN TERRE CRUE: DISPOSITIONS QUALITATIVES, CONSTRUCTIVES ET ARCHITECTURALES," 2015.

[18] H. Binici, O. Aksogan, and T. Shah, "Investigation of fibre reinforced mud brick as a building material," Constr Build Mater, vol. 19, no. 4, pp. 313–318, May 2005, doi: 10.1016/j.conbuildmat.2004.07.013.

[19] Geo engineer, "Step-by-Step Guide for Grain Size Analysis." Accessed: Sep. 07, 2023. [Online]. Available: https://www.geoengineer.org

[20] M. «Achenza and U. «Sanna, Il manuale tematico della terra cruda. 2006.

[21] M. F. Sabbà, M. Tesoro, C. Falcicchio, and D. Foti, "Rammed Earth with Straw Fibers and Earth Mortar: Mix Design and Mechanical Characteristics Determination," Fibers, vol. 9, no. 5, p. 30, May 2021, doi: 10.3390/fib9050030.

[22] E. OZBEK, G. PALESTRA, and C. ROSSI, "Ricerca sulla terra cruda come materiale costruttivo contemporaneo e versatile, applicata al progetto per la nuova scuola di Korofina a Bamako DAYÈ LÈ KOGO - Relazione," 2022.

[23] M. Bouhicha, F. Aouissi, and S. Kenai, "Performance of composite soil reinforced with barley straw," Cem Concr Compos, vol. 27, no. 5, pp. 617–621, May 2005, doi: 10.1016/j.cemconcomp.2004.09.013.

[24] Ş. Yetgin, Ö. ÇAVDAR, and A. Çavdar, "The effects of the fiber contents on the mechanic properties of the adobes," Constr Build Mater, vol. 22, no. 3, pp. 222–227, Mar. 2008, doi: 10.1016/j.conbuildmat.2006.08.022.

IV. GUIDELINS AND OBJECTIVES

[1] Balouo Salo, "Our mission: to improve the world." Accessed: Feb. 10, 2023. [Online]. Available: https://www.balouosalo.com/

[2] Kaira Looro, "KAIRA LOORO - ARCHITECTURE FOR PEACE - ARCHITECTURE COMPETITION." Accessed: Mar. 20, 2023. [Online]. Available: https://www.kairalooro.com/

V. ARCHITECTURAL DESIGN

[1] A. Rojas, "A vernacular paradigm in Senegal, Fass School and Teachers' Residence by Toshiko Mori ." Accessed: Mar. 31, 2023. [Online]. Available: https://www.metalocus.es

[2] Toshiko Mori Architects, “Fass School and Teachers’ Residence.” Accessed: Apr. 03, 2023. [Online]. Available: https://tmarch.com/fass

[3] Far.ms, “ANANDALOY.” Accessed: Nov. 03, 2023. [Online]. Available: https://far-ms.com

[4] Studio Anna Heringer, “Anandaloy: Centre for People with disabilities + Dipdii Textiles studio.” Accessed: Apr. 08, 2023. [Online]. Available: https://www.anna-heringer.com/projects/anandaloy/

[5] Kere Architecture, “Dano Secondary School.” Accessed: Apr. 08, 2023. [Online]. Available: https://www.kerearchitecture.com

[6] N. Navone, “BSI Swiss Architectural Award 2010.” Accessed: Sep. 04, 2023. [Online]. Available: https://www.architecturalrecord.com

[7] DAWOFFICE, “ESCUELA SECUNDARIA CEM KAMANAR.” Accessed: Apr. 04, 2023. [Online]. Available: https://dawoffice.com

[8] Foundawtion, “ Collège CEM Kamanar .” Accessed: Apr. 04, 2023. [Online]. Available: https://foundawtion.org

[9] Arquitectura Viva, “Kamanar Secondary School, Thionck Essyl.” Accessed: Apr. 10, 2023. [Online]. Available: https://arquitecturaviva.com

[10] MASS., “Maternity Waiting Village.” Accessed: Aug. 31, 2023. [Online]. Available: https://massdesigngroup.org

[11] Kere Architecture, “Lycée Schorge.” Accessed: Apr. 11, 2023. [Online]. Available: https://www.kerearchitecture.com

[12] H. Gryc and J. da Silva, “Global engineers thinking locally: creating kindergartens for Africa,” Aug. 2013. doi: 10.1680/cien.12.00042.

[13] ARUP, “A prototype kindergarten for a remote district of Ghana.” Accessed: Nov. 03, 2023. [Online]. Available: https://www.arup.com

[14] C. Nicholas, “The Econef Children’s Center - Sustainable architecture for a sustainable future.” Accessed: Sep. 04, 2023. [Online]. Available: https://www.asante.se

[15] D. Gauzin-Müller, Architecture en terre d’aujourd’hui. 2017.

VI. CONSTRUCTION DETAILS

[1] M. Achenza and U. Sanna, il manuale tematico della terra cruda. 2006.

[2] United Nations Center for Human Settlements (Habitat), Earth construction technology. 1992.

[3] G. Minke, Building with earth. 2006.

[4] R. Anger and L. Fontaine, Bâtir en terre : du grain de sable à l’architecture. 2009.

[5] Center for the Development of Industry and CRATerre, “Compressed earth blocks standards,” 1998.

[6] C. Jayasinghe, H. D. D. Lakmali, and M. P. Rohita, “Comparative Performance of Masonry Bond Patterns,” 2008.

[7] G. Minke, Earth Construction Handbook. 2000.

[8] Confédération de la construction en terre crue, Guide des bonne pratiques de la construction brique de terre crue. 2020.

VII. STRUCTURAL DESIGN

[1] Cycle Terre, "GUIDE DE CONCEPTION ET DE CONSTRUCTION - CAHIER 2 Les Blocs de Terre Comprimée," May 2021.

[2] "L'atlas des bois tropicaux - Ayous." 2016.

[3] "EUROCODE 3 : Table of design material properties for structural steel."

[4] K. Mallikarjun, "Alternate roofing." Accessed: Oct. 29, 2023. [Online]. Available: https://www.slideshare.net

[5] A. Shah-Bhimjyani, "An airy Raipur bungalow that unveils a charming courtyard." Accessed: Nov. 06, 2023. [Online]. Available: https://www.architecturaldigest.in

[6] M. R. Maheri, S. Pourfallah, and R. Azarm, "Seismic retrofitting methods for the jack arch masonry slabs," Eng Struct, vol. 36, pp. 49–60, Mar. 2012, doi: 10.1016/j.engstruct.2011.11.018.

[7] J. Halkyard, "Floating Offshore Platform Design," in Handbook of Offshore Engineering, Elsevier, 2005, pp. 419–661. doi: 10.1016/B978-008044381-2.50010-2.

[8] Ministero delle infrastrutture e dei trasporti, "NTC 2018 - Valori caratteristici di resistenza del legno," 2018. [Online]. Available: http://www.sttan.it

[9] Conseil d Administration de l'Association Sénégalaise de Normalisation, "NS 02-058 - Règles SENEVENT - Méthode d'évaluation des efforts du vent sur les constructions au Sénégal," 2008.

[10] Universita di Catania, "Carico da vento." Accessed: Oct. 28, 2023. [Online]. Available: http://www.dica.unict.it

[11] "Table of design properties for flanged steel profiles (IPE, HEA, HEB, HEM, UB, UC, UBP)." Accessed: Oct. 10, 2023. [Online]. Available: https://eurocodeapplied.com

[12] The European Union Per Regulation, "Eurocode 6: Design of masonry structures - Part 1-1: General rules for reinforced and unreinforced masonry structures," 2005.

[13] J. Halkyard, "Floating Offshore Platform Design," in Handbook of Offshore Engineering, Elsevier, 2005, pp. 419–661. doi: 10.1016/B978-008044381-2.50010-2.

[14] C. Nazionale and D. Ricerche, "CNR-DT 207/2008 Istruzioni per la valutazione delle azioni e degli effetti del vento sulle costruzioni," 2019.

VIII. PASSIVE DESIGN

[1] F. Butera, R. Adhikari, N. Aste, and United Nations Human Settlements Programme, Sustainable building design for tropical climates : principles and applications for eastern Africa. 2014.

[2] Agence régionale de l'environnement et des nouvelles énergies (Ile-de-France), "Confort thermique passif."

[3] S. Dhaka, J. Mathur, G. Brager, and A. Honnekeri, "Assessment of thermal environmental conditions and quantification of thermal adaptation in naturally ventilated buildings in composite climate of India," Build Environ, vol. 86, pp. 17–28, Apr. 2015, doi: 10.1016/j.buildenv.2014.11.024.

[4] Agence régionale de l'environnement et des nouvelles énergies (Île-de-France), V.-M. Institut pour la conception environnementale du bâti (Ivry-sur-Seine, and Impr. Caractère), Ventilation naturelle et mécanique. ARENE Île-de-France, 2012.

[5] A. Aflaki, N. Mahyuddin, Z. Al-Cheikh Mahmoud, and M. R. Baharum, "A review on natural ventilation applications through building façade components and ventilation openings in tropical climates," Energy and Buildings, vol. 101. Elsevier Ltd, pp. 153–162, Jul. 28, 2015. doi: 10.1016/j.enbuild.2015.04.033.

[6] J.-P. Bourdier and M. Trinh, Habiter un monde: Architectures de l'Afrique de l'Ouest. 2005.

[7] G. Giuffrida, R. Caponetto, and F. Nocera, "Hygrothermal properties of raw earth materials: A literature review," Sustainability (Switzerland), vol. 11, no. 19. MDPI, Oct. 01, 2019. doi: 10.3390/su11195342.

[8] G. Minke, Building with earth. 2006.

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

[10] Programme for Energy Efficiency in Buildings (PEEB), "FEUILLE DE ROUTE POUR UNE FUTURE REGLEMENTATION ENERGETIQUE ET ENVIRONNEMENTALE DANS LE SECTEUR DU BATIMENT AU SENEGAL," 2021. [Online]. Available: https://www.peeb.build/fr/about-peeb

[11] T. Joffroy, A. Misse, R. Celaire, and L. Rakotomalala, "Architecture bioclimatique et efficacité énergétique des bâtiments au Sénégal," 2019. [Online]. Available: https://hal.science/hal-02025559

[12] Y. Sane et al., "Intensity-duration-frequency (IDF) rainfall curves in Senegal," Natural Hazards and Earth System Sciences, vol. 18, no. 7, pp. 1849–1866, Jul. 2018, doi: 10.5194/nhess-18-1849-2018.

IX. REASEARCH ON BIO-BRICKS

[1] G. Aubert and P. Segalen, "PROJET DE CLASSIFICATION DES SOLS FERRALLITIQUES."

[2] Hu Xinyue, "BIOBASED THERMAL-INSULAT-ING MATERIAL IN LOW-CARBON BUILDING CONSTRUCTION," 2022.

[3] M. Bourgeois, E. Coquillart, M. Cournarie, and C. Fassino, "Sol." Accessed: Sep. 07, 2023. [Online]. Available: https://www.supagro.fr

[4] W. Carazas Aedo, "TEST CARAZAS Manual pedagógico," 2017.

[5] S. S. D. Raavi and D. D. Tripura, "Ultrasonic pulse velocity and statistical analysis for predicting and evaluating the properties of rammed earth with natural and brick aggregates," Constr Build Mater,

vol. 298, p. 123840, Sep. 2021, doi: 10.1016/j.conbuildmat.2021.123840.

[6] Pavi Bambu, "Pavimenti in Bambu." Accessed: Sep. 20, 2023. [Online]. Available: https://www.pavibamboo.com

[7] G. Lemmi, "Case di paglia: tecnologia, isolamento e posa in opera ." Accessed: Sep. 20, 2023. [Online]. Available: https://www.teknoring.com

[8] St. J. The American Society of Agricultural and Biological Engineers, "Bulk density of wet and dry wheat straw and switchgrass particles." Accessed: Sep. 17, 2023. [Online]. Available: https://elibrary.asabe.org

[9] RFCP, "Caractéristiques techniques." Accessed: Sep. 09, 2023. [Online]. Available: https://www.rfcp.fr

[10] E. Meier, "Pine Wood: An Overall Guide." Accessed: Sep. 12, 2023. [Online]. Available: https://www.wood-database.com

[11] Ş. Yetgin, Ö. ÇAVDAR, and A. Çavdar, "The effects of the fiber contents on the mechanic properties of the adobes," Constr Build Mater, vol. 22, no. 3, pp. 222–227, Mar. 2008, doi: 10.1016/j.conbuildmat.2006.08.022.

[12] M. «Achenza and U. «Sanna, Il manuale tematico della terra cruda. 2006.

[13] M. Bouhicha, F. Aouissi, and S. Kenai, "Performance of composite soil reinforced with barley straw," Cem Concr Compos, vol. 27, no. 5, pp. 617–621, May 2005, doi: 10.1016/j.cemconcomp.2004.09.013.

[14] T. L. Piani, D. Krabbenborg, J. Weerheijm, L. Koene, and L. J. Sluijs, "THE MECHANICAL PERFORMANCE OF TRADITIONAL ADOBE MASONRY COMPONENTS: AN EXPERIMENTAL-ANALYTICAL CHARACTERIZATION OF SOIL BRICKS AND MUD MORTAR," Journal of Green Building, vol. 13, no. 3, pp. 17–44, Jun. 2018, doi: 10.3992/1943-4618.13.3.17.

[15] Center for the Development of Industry and CRATerre, "Compressed earth blocks standards," 1998.

[16] Horst Schroeder, "The New DIN Standards in Earth Building—The Current Situation in Germany," Journal of Civil Engineering and Architecture, vol. 12, no. 2, Feb. 2018, doi: 10.17265/1934-7359/2018.02.005.

[17] H. Limami, I. Manssouri, K. Cherkaoui, and A. Khaldoun, "Mechanical and physicochemical performances of reinforced unfired clay bricks with recycled Typha-fibers waste as a construction material additive," Clean Eng Technol, vol. 2, p. 100037, Jun. 2021, doi: 10.1016/j.clet.2020.100037.

[18] H. Limami, I. Manssouri, K. Cherkaoui, and A. Khaldoun, "Mechanical and physicochemical performances of reinforced unfired clay bricks with recycled Typha-fibers waste as a construction material additive," Clean Eng Technol, vol. 2, p. 100037, Jun. 2021, doi: 10.1016/j.clet.2020.100037.

[19] Horst Schroeder, "The New DIN Standards in Earth Building—The Current Situation in Germany," Journal of Civil Engineering and Architecture, vol. 12, no. 2, Feb. 2018, doi: 10.17265/1934-7359/2018.02.005.

[20] Maignien and Roger, "Les sols des plaines alluviales de la Casamance aux environs de Sedhiou," 1961.

X. LIFE CYCLE ASSESSMENT

[1] W. Klöpffer and B. Grahl, Life Cycle Assessment (LCA): A Guide to Best Practice, John Wiley & Sons. 2014.

[2] M. Z. Hauschild, R. K. Rosenbaum, and S. I. Olsen, "Life Cycle Assessment."

[3] European Commission - Joint Research Centre - Institute for Environment and Sustainability (JRC-IES), ILCD Handbook General guide for LCA. 2010.

[4] ecoinvent, "About ecoinvent." Accessed: Nov. 14, 2023. [Online]. Available: https://ecoinvent.org/the-ecoinvent-association/

[5] One Click LCA Ltd, "What data is available in One Click LCA?" Accessed: Nov. 14, 2023. [Online]. Available: https://www.oneclicklca.com/support/faq-and-guidance/documentation/database/

[6] E. Hoxha et al., "Biogenic carbon in buildings: a critical overview of LCA methods," Buildings and Cities, vol. 1, no. 1, pp. 504–524, 2020, doi: 10.5334/bc.46.

[7] G. Guest, F. Cherubini, and A. H. Strømman, "Global Warming Potential of Carbon Dioxide Emissions from Biomass Stored in the Anthroposphere and Used for Bioenergy at End of Life," J Ind Ecol, vol. 17, no. 1, pp. 20–30, 2013, doi: 10.1111/j.1530-9290.2012.00507.x.

[8] ecoinvent, "System Models." Accessed: Oct. 07, 2023. [Online]. Available: https://ecoinvent.org/the-ecoinvent-database/system-models/

[9] Briques Technic Concept and Cycle Terre, "FDES Paroi en Bloc de Terre Comprimée porteuse," 2021.

[10] Filiater, "FDES Mur en brique de terre compressée," 2020.

[11] D. Arduin, L. R. Caldas, R. de L. M. Paiva, and F. Rocha, "Life Cycle Assessment (LCA) in Earth Construction: A Systematic Literature Review Considering Five Construction Techniques," Sustainability (Switzerland), vol. 14, no. 20. MDPI, Oct. 01, 2022. doi: 10.3390/su142013228.

[12] G. Minke, Building with earth. 2006.

[13] P. Pasanen and R. Castro, "Carbon Heroes Benchmark Program-whole building embodied carbon profiling," 2019.

[14] 2000-Watt Society, "Handbuch zum Zertifikat 2000-Watt-Areal," 2021.

[15] Ministère français du logement et de l'habitat durable and Ministère français de l'environnement de l'énergie et de la mer, "Référentiel « Energie-Carbone » pour les bâtiments neufs Niveaux de performance « Energie-Carbone » pour les bâtiments neufs," 2016.

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