Climate and employment impacts of sustainable building materials in the context of development cooperation

Published by:

Deutsche Gesellschaft
für Internationale
Zusammenarbeit (GIZ) GmbH

As a federally owned enterprise, GIZ supports the German Government
in achieving its objectives in the field of international cooperation for
sustainable development.

Published by:
Deutsche Gesellschaft für
Internationale Zusammenarbeit (GIZ) GmbH

Registered offices
Bonn and Eschborn, Germany

Address
Friedrich-Ebert-Allee 32 + 36
53113 Bonn, Germany
T +49 228 44 60-0
F +49 228 44 60-17 66

Dag-Hammarskjöld-Weg 1 - 5
65760 Eschborn, Germany
T +49 61 96 79-0
F +49 61 96 79-11 15

E info@giz.de
I www.giz.de/en

Sector Programme Cities

Responsible:
Esther Moltie
Milena Wald
Anastasiya Shadkhina.

Authors:
Hannah Langmaack
Peter Scheibstock
Sophia Schmuck
Thomas Kraubitz

BURO HAPPOLD

Layout & graphics:
Michał Werder

Photo credits/sources:
Adobe Stock or with credits mentioned under the photos.

Acknowledgment for expert inputs:
Wolfram Schmidt, Werner Theuerkorn, Martin Krus, Theo Großkinsky,
Tea Kufringer, Ernest Dione, Anna Heringer, Robert Rösler,
Adelheid Wehmöller

On behalf of
German Federal Ministry for Economic Cooperation and Development (BMZ)

Bonn 2021

Abbreviations

AAC	Autoclaved Aerated Concrete
BMZ	German Federal Ministry of Economic Cooperation and Development
CEB	Compressed earth block
CLT	Cross laminated timber
CO_2	Carbon dioxide
CO_2e	CO_2 equivalent
DC	Development cooperation
FA	Fly ash
GGBS	Ground granulated blast furnace slag
GHG	Greenhouse gas
GLULAM	Glued laminated timber
MPa	Mega Pascal
NSW	New South Wales
OPC	Ordinary Portland Cement
PET	Polyethylene terephthalate
RCC	Reinforced cement concrete
RE	Rammed earth
RHA	Rice husk ash
SCMs	Supplementary cementing materials
SRE	Stabilised rammed earth
TOR	Terms of Reference

Contents

Executive Summary

The built environment accounts for 38% of global GHG emissions. The construction sector must take urgent action to limit its impact on climate change. Carbon emissions occur through fossil energy consumed in building operation, and through embodied energy occurring through extraction, processing, transportation, construction and disposal of materials for construction such as steel, concrete and aluminium. While operational emissions have been in the focus of global policies, embodied emissions in the building sector are slowly gaining momentum. With a share of around 11% of the annual global GHG emissions, they are highly relevant to substantially reduce the carbon footprint of the sector. Changing industrial and societal practices to successfully transition to sustainable ways of construction is therefore of central importance. Although sustainable building materials are gaining more importance as an alternative or supplementary option to conventional materials, knowledge gaps remain when it comes to their implementation and mitigation impacts.

This report builds on desk research, industry practice, expert interviews, and case studies from across the sector and around the world to contribute to a better understanding of the impacts of construction materials used in the industry, associated carbon emissions, and alternatives to commonly used building materials. Ten alternative materials have been assessed within the study covering renewable and recycled materials, clay, alternative concrete and cement, as well as alternative building techniques. The materials range from established products such as mass timber and bamboo to less established or pioneering materials such as typha, agro-based cementitious additions to concrete. In the material profiles, the GHG and environmental impacts are evaluated as well as the suitability for the construction of different urban typologies and possibilities of closed loop production. The manufacturing and employment impacts are discussed in the context of development cooperation in the Global South.

The study finds that transitioning towards a more sustainable building sector requires careful assessment and selection of sustainable options depending on their suitability for the respective project typology, climate mitigation potential, and circularity at end-of life of the building. While some materials such as concrete with SCMs and rammed earth have a high compressive strength and can be used for load-bearing applications, materials such as straw bales are better suited for low rise buildings or interior partition walls. Because not all materials can fulfil the requirements for all building types, especially for specific urban typologies and high-rise buildings, a mix of conventional materials and sustainable materials is often necessary. Value chains and production processes of materials such as timber showed that even ideal sustainable materials are not always the best choice as raw material or natural product are of limited availability in some regions. Flexibility and local interest of communities and authorities in many counties of the Global South can be beneficial when it comes to local norms and regulations for introducing new products, opening up prospects for developing new markets and employment opportunities.

The assessed materials show that while there are several opportunities, also many challenges remain for mainstreaming sustainable, low-carbon construction materials. A bottleneck for implementing and upscaling includes the lack of awareness and technical knowledge on how to utilise such materials appropriately and plan for maintenance and repair of materials and building elements. In addition, reliable, regional information on embodied emissions of different types of building materials remains a persistent challenge and calls for future projects to contribute to data collection to allow for transparency and accountability.

Rammed earth buildings in the Hacienda Santa Maria, Tarma, Junin, Pérou. Author: JYB Devot.
https://commons.wikimedia.org/wiki/File:PiseP1010653mod.jpg

Introduction

1 Introduction

1.1 Aim of the Study

The study aims to contribute to understanding the impacts of the construction industry on climate change and the relevance of embodied carbon emissions of building materials by providing more detailed information on CO_2 reduction potential as well as employment effects of various building materials. For the preparation of the study, a desk-research on secondary literature has been conducted and experts of Buro Happold's own network and BMZ's partner network have been consulted for additional inputs. The evaluations are presented in form of building material profiles, each of which is underpinned by an applicable example from Development Cooperation (DC) or by examples from the German BMZ partner network on sustainable buildings and construction. Recommendations are given to highlight overarching principles to be considered from stakeholders active in the context.

1.2 Relevance of the topic

With a share of 40% of annual global CO_2 emissions, the construction sector is contributing significantly to climate change. Of those total emissions, building operations are responsible for 28% annually, while building materials and construction activity are responsible for an additional 11% annually (WGBC, 2019). However, unlike operational carbon emissions, which can be reduced over time with improved energy efficiency and the use of renewable energy, embodied carbon emissions are locked in place as soon as a building is built. This means, embodied carbon stemming from the extraction, processing or manufacturing, transportation, construction or installation, and disposal of materials makes up a high share of a building's climate impact. Changing industrial and societal practices to successfully transition to sustainable ways of construction is therefore of central importance.

By 2060, the total floor area of buildings will double, with most of this new construction expected to happen in the Global South, mostly in Africa and Asia (UN Environment, 2017). With 60% of the building sector's emissions being associated with the production and delivery of building materials, tackling construction emissions becomes critical. Renewable, and often locally available building materials such as timber, clay or bamboo and innovations for conventional building materials offer enormous opportunities for a climate-friendly transition of the sector. However, to mainstream sustainable practices, the actual potential of CO_2 savings in sustainable materials needs to be further explored and disseminated to the sector's stakeholders. In line with keeping the global temperature rise to within 1.5ºC above pre-industrial levels, potentials of sustainable construction materials need to be further explored and sustainable practices mainstreamed. To draw on the potential of renewable and low-carbon materials, the quantifiable impacts in terms of reduced CO_2 emissions have to be further explored and reliable studies on CO_2 reductions of climate friendly materials are scarce.

In addition to the significant potential for mitigating greenhouse gas (GHG) emissions, clean construction strategies are likely to initiate changes in the current supply chain and economic structure of the construction industry. In this study, qualitative and, if available, quantitative estimations are given, how specific building materials could potentially impact local labour markets. However, as only a few studies have intended to model the effects of employment effects and general data is scarce, these employment potentials of the construction sector have to be further assessed along local value chains.

1.3 Influence of building materials on global warming

In scientific literature, there is consensus that within building materials, concrete, steel, glass and aluminium contribute the most to climate change globally. The manufacture of these materials for use in building construction accounts for around 11% of global CO_2 emissions (WGBC, 2019). Concrete is the most consumed material in the sector, with twice as much concrete being used in construction as all other building materials combined. Due to its main ingredient cement, concrete is one of the most carbon intensive construction materials contributing to climate change with a share of around 5-8% of total emissions. Global cement consumption is projected to increase by 12-23% by 2050, while global steel production is forecast to grow by 30% over the same period (WGBC, 2019).

Overall, the global building sector's emissions increased over that last years and are likely to continue to do so. While efficiency improvements continue to be made, they are not adequate to outpace demand growth with emission increases driven by strong floor area and population expansions. To mitigate building emissions, greater attention is required on low-carbon building materials, and nature-based solutions (UN Environment, 2017).

1.4 Sustainable building materials in context of CO_2 reduction potential and employment promotion

With continuous and rapid urbanisation in many countries of the Global South it becomes inevitable to apply strategies to streamline climate friendly materials to reduce embodied carbon on a global scale. This can include using low carbon materials, using materials with lower carbon specification such as low carbon cement or 'green' steel, considering the manufacturing location of materials, preventing waste going to landfill or designing with materials for longevity. When assessing embodied carbon, the focus has largely been on efficiencies of industrial materials such as concrete and steel rather than on renewable, and often traditional materials used and available in regions of the Global South such as clay or bamboo. Natural materials are often renewable, better suited to local climatic conditions, generally lower in embodied energy and are less damaging to the environment since they require less processing. Local building materials further hold the benefit of reducing emissions from transports significantly.

In countries of the Global South, capital intensive, highly mechanised manufacturing processes of the large-scale construction sector are often particularly difficult to provide formal employment over long term. The employment and labour hurdles as well as skill demands surrounding the manufacturing processes of the construction sector hamper employment promotion and bring to question the issue of sustainability. Renewable building materials often require less processing and less skilled work and therefore hold a great potential regarding employment promotion along their value chains in countries of the Global South. Studies show that the use of local materials in the implementation of urban construction projects keeps the economic value locally in the best case over the whole value chain. Further, the use of local knowledge and vernacular architecture in many cases is more adaptable and sustainable in terms of indoor climate (passive strategies), choice of materials and costs.

In many countries, the building sector holds large potential for growth through a market shift towards green and sustainable construction techniques and materials. Sustainable materials can open opportunities for pioneer work, enabling small and medium enterprises (SMEs) as well as start-ups to enter a market usually run by established large-scale companies. New or different uses of materials such as non-commercially used agricultural by-products can create new demands and markets supporting formal and informal employment. However, major changes within the industry though are only taking up at a slow pace, as local value chains, established design processes, and skills require adaptions and redevelopments. It is important to note, that for most industrial sectors producing construction material insufficient data is available to quantify benefits and impacts and knowledge gaps remain, especially for the context of the Global South.

2 Methodology

Assessing building materials regarding their sustainability is a complex issue touching on a broad range of sectors and interdependencies. It requires a sound baseline to depart from current standards towards solutions that create long-term value for all stakeholders involved. For this study, a desk review of secondary literature, and consultations with stakeholders and experts of Buro Happold's own and BMZ's wider partner networks have been carried out to gain insights from different perspectives and industries. The process for the study involved three steps and included

- the selection of appropriate climate friendly materials for the context of the Global South (2.1);
- a literature review and expert interviews, as well as (2.2)
- the building material profiling (2.3)

2.1 Material Selection Criteria

The examination of enabling conditions for sustainable building materials requires a logical, evidence-based approach. With vast variants of building materials available globally and each of them having their individual strengths and weaknesses, often being restricted to particular regions, material selection criteria have been developed by the authors, to allow for an informed and transparent process of choosing a set of materials for the profiles.

These criteria (shown in Table 1) reflect the aim of the study by focussing on climate impacts, transferability to different regions and geographic conditions as well as on local employment effects. Further to that, the material selection criteria involve market presence, cost and circularity of the materials to ensure reliability, knowledge in maintenance or cost efficiency. Lastly, process sophistication, scalability and resource intensity were included as criteria to avoid including energy, water, or material intense construction materials. Eventually, as a general baseline, all aspects considered in the study have to be viable and beneficial for the context of the Global South, with often hot and humid climates.

After developing the selection criteria, those were then prioritised to give more relevant criteria more weight in the selection process. The assessment has been carried out through screening of quantitative and qualitative data. The then shortlisted materials were assessed and classified according to their characteristics and lastly ranked and selected. The material shortlist consisting of 15 materials was communicated mid-July 2021 to GIZ's project team, discussed and commonly agreed in order to select 10 materials for the profiles. The following table shows the selection criteria and their definition.

Priority	Criteria	Criteria definition
1	Availability of raw materials	The material should be sourcable over several regions rather than being available only locally. Worldwide also includes a specific climate in different global regions (humid climate, etc.)
1	Climate Impact	The material should hold significant (measurable) climate benefits over conventional construction materials.
1	Employment impact	Impacts of production, manufacturing and usage of the material on local employment.
2	Market Presence	Construction materials should have an established market to minimise risks of lack of supply, knowledge in maintenance, cost efficiency, reliability, etc.
2	Cost	Consumer cost, estimated based on material price (low to high and how many raw materials are needed), sophistication of production/processing (manual labour to advanced technology) and necessity of technical staff (untrained to highly trained staff)
2	Closed Loop Manufacturing (Circularity)	Circularity potential of materials (reusability, recycling/downcycling, recovery/disposal). Hazardous materials and residues such as glues etc. should be minmised and possible to remove before reuse.
3	"Production/ Manufacturing"	Process sophistication. Balancing mechanised and manual operation processes to optimise efficiency of production systems.
3	Resource Intensity	Intensity of necessary resources (e.g. materials, energy and water) required for the provision of a unit of a good or service.
3	Scalability	Market capability to adapt easily to increased workload or market demands. Depends on how established raw materials and production are.

Table 1 Selection Criteria

Exceeds Criteria	Meets Criteria	Below Criteria	Comments
Worldwide	Regional	Local	Timber would be regional since not available or sustainable to use in all climates and regions worldwide. Recycled plastic would be worldwide as this material is available in all regions.
Significant benefits	Medium	Low	Climate impact related to material group (load-bearing, insulating, etc.)
Positive impacts on employment opportunities	Medium impacts on employement opportunities	Negative impacts on employment opportunities	Example: Recycled materials can contribute to creating new markets for otherwise unused waste materials such as plastic, concrete or paper.
Established	Recent	Pioneer	Pioneer includes new materials using new and not established techniques. Recent includes new materials with established/ known technology. Established are known and widely used technologies and established materials.
Low	Medium	High	Example: Rammed earth using untrained staff and low cost raw material would be classified as low, while timber can only be harvested after some years and needs processing and manufacturing by trained staff. Timber would be classified as high.
"Closed loop possible/ Compostable"	"Recycling/ downcycling"	"Recovery/ Disposal"	
Balanced mechanised and manual operation processes	Complex or highly mechanised operation processes	Highly complex process	To what extent are trained staff, machines and advanced technologies necessary?
Low	Medium	High	
High	Medium	Low	Example: 3D printing with clay uses established low cost material but scalability remains low due to advanced technology with the necessaity for highly trained staff.

2.2 Literature Review and Expert interviews

A literature review has been conducted in order to provide an overview of current knowledge on selected materials, relevant research and gaps for further assessments. Priority has been given to reliable sources such as peer reviewed articles and published reports. However, as many of the selected materials are still emerging on small scale and their climate and employment impact is often not well documented publicly, expert interviews have been carried out additionally to collect further information.

The following experts have been interviewed by the authors through in-person and virtual interviews:

- Wolfram Schmidt (BAM)
  Supplemental Cementitious Materials and Concretes
- Werner Theuerkorn (Fraunhofer Institute)
  Typha and biobased materials
- Martin Krus (Fraunhofer Institute)
  Typha and biobased materials
- Theo Großkinsky (Fraunhofer Institute)
  Typha and biobased materials
- Tea Kufringer (LEVS Arkitekten)
  Clay and compressed earth blocks
- Ernest Dione (Typha Expert)
  Typha in the Senegalese border region
- Anna Heringer (Architect)
  Clay and rammed earth
- Robert Rösler (Polycare)
  Polymer Concrete
- Adelheid Wehmöller (MISEROR)
  Sustainable Construction Materials in the development context

2.3 Classification of building materials

A total of 10 material profiles have been prepared consisting of the following components:

Material Overview

The material overview consists of a summary of the production process of the material including regional availability of the raw materials or environmental conditions for cultivation as well as properties and potential applications. The general classification further describes the suitability for dense urban structures and urban typologies, based on limitations of the materials regarding feasibility of building masses/heights, durability and suitability for climates and weather resistance.

GHG and environmental impacts

This section of the building profiles aims to provide an estimation on overall GHG balances, focused on CO2, including local emissions resulting from production and emissions caused by transportation processes of the material. If quantifiable data is available for the respective material and context, GHG emissions are mapped out as CO_2-equivalents (CO_2eq). In addition, other environmental impacts and influences on micro- and meso-climate due to cultivation and extraction as well as production processes and water consumption are highlighted in this section if applicable.

Suitable use for construction

As different sustainable building materials are suited for varying building typologies, this section gives an overview on suitable areas of application. This includes the assessment of suitable floor heights, number of floors (low-rise vs. high-rise typologies), maintenance requirements as well as the estimated life span of the buildings or building components. Also, if available, insights of the proportional costs for construction and maintenance are provided.

Production, process and employment effects

A summary on employment effects is given in this section by providing insights on potential of local production of the respective building material along the value chains including construction by local companies and maintenance. To assess the materials over their whole life cycle, including production and labour processes, this section consists of a schematic presentation of the value chains based on basic production and transport processes. Quantitative approximations are given where available, however with regionally diverse markets and scarce data on labour impacts, numbers provided in this study are highly indicative.

Where data is available, the employment effects will include information on characteristics of the generated employment potential including qualification and training requirements, seasonality, gender effects, quality of jobs or effects on formality/informality of employment. The section further aims to cover any possible negative externalities (e.g., job losses in conventional construction production in the Global South, loss of jobs in the logistics chain, etc.).

Circularity

This section covers the potential of materials to be reused, recycled/downcycled, recovered or disposed at end-of-life. Ideally, materials should not contain hazardous materials and residues such as glues etc. should be minimized and possible to remove before reuse. Circularity builds an important element to assess as the reusability and recyclability of materials to reduce the need for future virgin materials and thereby reduce the carbon and resource footprint for energy intensive production processes.

Case Study

Practical examples are provided for each building material through showcases of built projects. While some case studies are located in Africa, Asia and Latin America, other examples are given from European and North American projects. If available, GHG and employment impact of the examples is quantified and illustrated based on interviews with stakeholders associated with the project.

Material Overview	**Production of the material**
	Regional location of the raw materials; Enviromental condition for cultivation
	Properties and potential applications
	Suitability for dense urban structures and urban typologies
	feasibility of building masses/heights; durability; suitability for climates; weather resistance
GHG and environmental impacts	**Overall CO_2**
	including local emissions resulting from production; Emissions caused by transportation processes
	Other impacts on micro- and meso- climate due to cultivation and extraction as well as production processes, water consumption
	other GHG than CO2; environmental impacts
Suitable use for construction	**Suitable areas of application**
	feasibility of building masses/heights; maintenance requirements; estimated life span of the building of building components
	overview of the proportional costs for construction and maintenance
Production, process and employment effects	**Schematic presentation of the value chains based on basic production and transport processes**
	Characteristics of the generated employment potential
	qualification and training requirements; gender effects; quality of jobs; seasonality
	possible negative externalities; effects on formality/informality of emploment
Circularity	**Circular potential of material**
	reuse; recycling/downcycling; recovery; disposal at end-of-life
Case Study	**Urban application example from at least one country of the Global South**

Figure 1 Sections of material profiles

3 Building material profiling

Chapter 3 aims to build a robust knowledge base for the recommendation of sustainable building materials for the context of the construction sector in the Global South. This section has been carried out by using desktop research to generate building material profiles to strengthen the evidence of data by quantifying, classifying and illustrating climate and employment impacts of selected building materials.

Overview Case Studies

Bamboo, Mexico

Mass timber building, Hawaii

Compressed earth blocks, Mali

Typha boards, Germany

Straw bale house, Nepal

Rammed earth, Bangladesh

Fly ash SCM, South Africa


Polymer concrete family house, Namibia

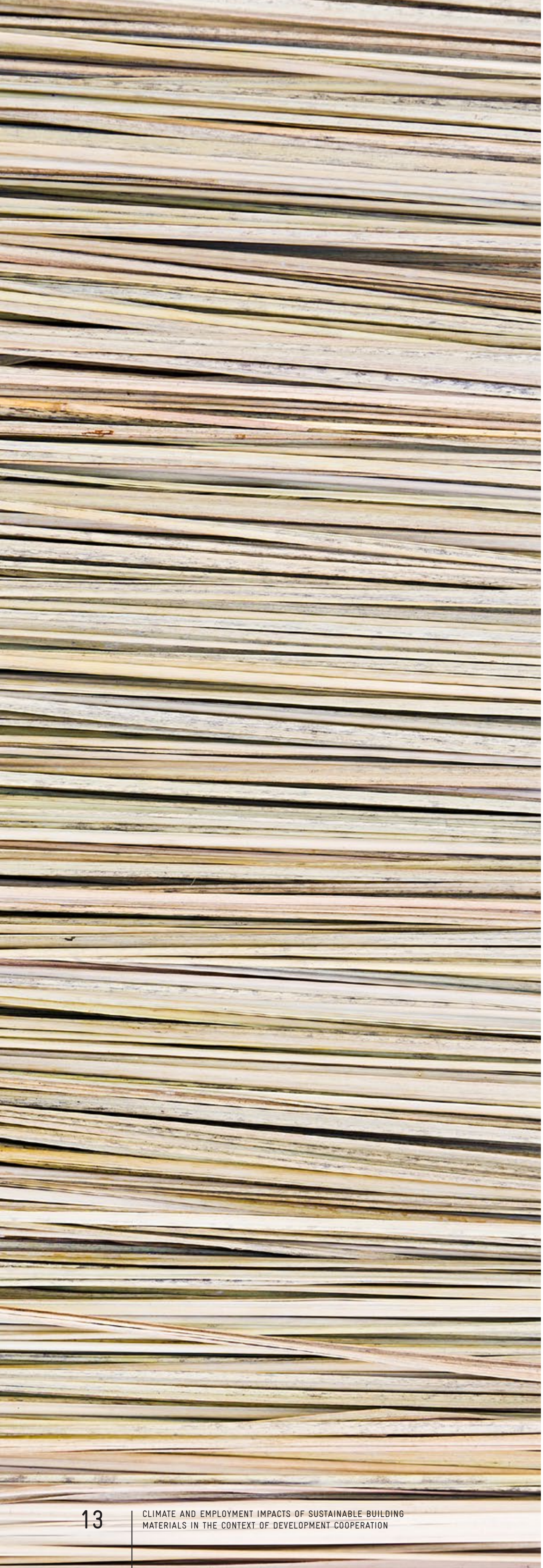

Recycled bricks, Australia


3D Lavacrete, Mexico


3D Clay, Italy

3.2 Organic building materials from renewable raw materials

The following section focuses on organic building materials from renewable raw materials including timber, bamboo, typha and straw bales. Within the building sector, timber and bamboo are amongst the most traditional construction materials and are seen to hold great climate mitigation potentials as trees and plants function as natural carbon sinks before construction and capture carbon throughout their lifetime as construction materials.



Typha

Material Overview

Typha describes a group of aquatic or semi-aquatic plants (also often referred to as cattail) distributed worldwide, ranging from temperate climate zones to tropical regions, where they can be found in a variety of wetland habitats. Due to its global availability, enormous yield, and economic efficiency, typha is predestined as a sustainable raw material for industrial application. Typha crops are insensitive, long-term, and natural monocultures, producing up to 25 tons dry matter per hectare annually (Krus, 2021). Typha plants are very dense and fast growing. Although the roots only grow up to 2-3 years, they build up to 35 plants per season on a space of 1 – $2m^2$. While timber is harvested typically once every 20 years, typha is harvested annually. The typha harvest volume per hectare is therefore, significantly higher than the timber harvest volume per hectare.

The creation of typha fields is associated with a variety of positive ecological effects. Planting typha can enhance water purification in case of over-fertilization or pollution, protect against soil erosion, contribute to create water retention areas and flood plains as well as valuable biotopes for fauna typical of fenlands (Krus, n.d., IPB Fraunhofer). In some regions, especially the wetland region between Senegal and Mauretania, typha is growing uncontrollably, hindering rice cultivation. Using typha as a building material could open new modes of income for the population and create a synergy effect to use the otherwise non-commercially used typha plants.

Due to its special structural properties, typha allows the production of building materials offering a combination of insulation and load-bearing effect at the same time. The particular suitability of the cattail leaf mass is based on the structure of the plant: the leaves have a fibre-reinforced, stable supporting tissue filled with a soft open-cell spongy tissue thus ensuring statics and an excellent insulation. The typha plate – a magnesite-bound, sustainable building material – represents an alternative to materials used in conventional building construction. Typha plates allow slim wall structures, perform static functions as well as thermal, moisture and fire protection tasks at once.

GHG and Environmental Impacts

As a semi-aquatic or aquatic plant, typha crops function as a carbon sink as they are growing as well as to the bonding of CO_2 when typha is grown on fen soils. A typha plantation can therefore serve as a CO_2 sink but also has further environmental advantages as it functions as a nutrient trap, as well as erosion barrier for water retention, flood plains and biotope formation. Further, the production process of construction material made from typha, such as blocks, boards or roofing material, does not involve energy intense processes. When grown and used in wetland areas, typha can be considered as a regional product involving short transport processes, avoiding transport induced GHG emissions, which make up the largest share of emissions in the typha value chain.

In the context of insulation, the insulating properties of typha help improve interior comfort for buildings but also reduce the energy use for air conditioning. A study in Senegal showed that typha insulation can have a 30% reduction on energy consumption which for an administrative building with 100 air conditioning units could result in a potential reduction of 14.7 tonnes of CO_2eq per year. Typha is therefore also of ecological interest in terms of reducing energy consumption and CO_2 emissions by improving their thermal insulation properties (CRA Terre, 2014). The heat transfer coefficient of typha boards is estimated to be between 0.45 - 0.55 W/(m^2.K). In a study for the renovation of a half-timbered house, the thermal insulation was measured with 0.35 W/(m^2.K) for a wall of 20 cm thickness.

Suitable use for construction

The plant's structure entails the particular suitability of the typha leaf mass for creating building materials. Typha can be used in form of blocks, as panels for partitions, wall linings or roofs. Typha blocks are utilised both for inner and outer building envelopes. The use of typha for inner envelopes is more advantageous to obtain a maximum of thermal phase shift. Due to the combination of tensile strength of stem fibre and elastic sponge-like tissue, leaves are tear and break resistant, flexible and maintain their shape even in dried condition. Behaviour of leaf mass under tensile and compressive stress is completely different along the leaf ¬axis from base to tip than perpendicular to it: along the axis, the leaf material resists high compression loads of approximately 1 N/mm and even higher tensile stress. Perpendicular to this axis, elastic deformation sets in already at very low stress of 0.01 N/mm and predominantly remains in reversible ranges (Krus, Theuerkorn, Großkinsky, Georgiev, 2014).

As building material for roofs, typha can be used either as an underside treatment (such as corrugated sheet metal panels; under flat roofs), or as a direct roof treatment (roof tiles and/or typha panels alone, or typha stubble). Compared to roofs made from sheet metal often providing a life span of 5 years only, a thatched roof made of typha can extend the lifespan to 40 years (Dione, 2019).

Typhaboard © typha technik Naturbaustoffe / Fraunhofer Institute for Building Physics IBP
https://www.ibp.fraunhofer.de/en/projects-references/building-material-cattail.html

Typha offers a good level of protection against fire and noise. This specific set of properties makes typha seem almost predestined for use as a base material in the production of highly insulating building materials that are subject to high loads (Krus, 2013). However, although typha is an aquatic plant and is extremely resistant to fungal attack, after drying it is necessary to take care and protect this outer shell from rain since the vegetable fibres are not compatible with humidity (Dione, 2019).

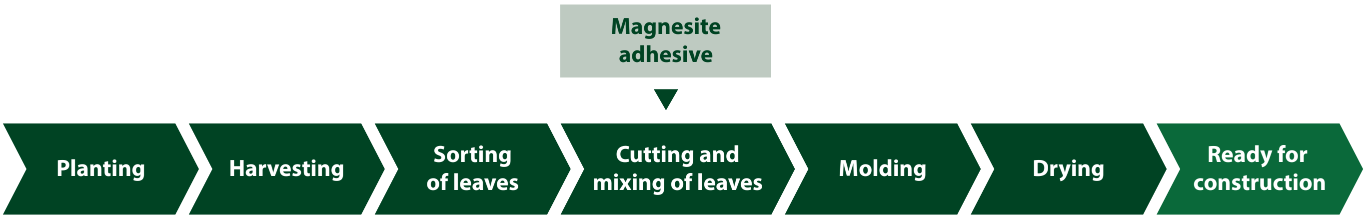


Figure 2 Manufacturing process of typha blocks

Production, process and employment effects

To produce typha blocks, the leaves are sorted, cut with parallel blades and shortened to the specific length required for the foreseen application. Once cut up, the desired quantity of particles is taken and put into a mixer, where they are sprayed with a predetermined amount of magnesite adhesive. The particles are then put into a mould, where they are compressed using a hot-pressing technique. The panels are dried out for a few days before they can finally be used in construction. Drying should take place over a period of 7 to 10 days with a humidity level between 12 and 14% (CRA Terre, 2014). In spite of the high stability of the panels following drying, they can easily be worked using standard tools. As magnesite is scarce in some regions and associated with comparably high cost, current research is looking into the potential using limestone as an alternative adhesive.

Typha offers economic and social benefits with potential for positive impacts on local employment and regional product supply. The plantation and harvest of typha can contribute to the creation of employment in structurally weak regions through income opportunities for small and medium-sized companies and agriculture. On the medium term, typha offers potentials for unsubsidised agriculture. Since the plant is relatively tolerant towards product fluctuations, it can easily build a second pillar of conventional agriculture or a third pillar for a regional product including a small-scale plant. Typha does not compete with food production (Krus, n.d., Fraunhofer IPB).

Typha is also considered an affordable material with one ton of dry typha reed at about 5000 West African Franc (CFA Franc), around 7€, per ton (Typha Terre, 2015). A person can cut 120 m^2 per day in high density areas, which corresponds to about two tons of green biomass. A mechanical harvest allows the harvest of 10 tons per hour. During drying, 120 tonnes of green material correspond to 20 tons of dry material. The reduction rate thus amounts to 1/6th of the mass.

Circularity

As Typha is a natural material, it provides a high returnability to the material cycle and can in most cases be composted after end of life (»Cradle to Cradle«). For typha blocks, only magnesite adhesives are added which make it possible to return typha blocks to the material cycle by dispensing with further additives such as biocides (Krus, n.d. Fraunhofer IPB).

Case Study:

Renovation of half-timbered house – Pfeifergasse 9

Location: Nuremberg, Germany

Architects/Developer: Altstadtfreunde Nürnberg e.V

Urban Typology: Residential

Year of construction: 2008

Materials: Typha panels, timber frame

Pfeifergasse 9 is a half-timbered house located in the Jakober quarter in the old town of Nuremberg. In the second World War 90% of the old town were destroyed, including most of the old buildings. Since 1973, the 'Altstadtfreunde Nürnberg e.V.' have been taking care of the preservation and reconstruction of the city. In 2008 they started to renovate the property at Pfeifergasse 9. The focus was on restoring the half-timbered appearance of the front building as a distinctive element of the city, with particular attention to ecological and energy-saving concepts. For this purpose, magnesite bonded typha panels were chosen, which offered several advantages.

The panels were used for compartment filling and for internal insulation of the solid masonry. The panels have a stiffening effect within the frame and support the load-bearing function of the truss. The installation proved to be simple, and the panels were easy to process with all common tools. The moderate thickness of the Typha boards (40 mm – 60 mm) for the interior insulation allowed for a thin wall construction. The good fire protection properties of the Typha material, its high insulating effect and its low susceptibility to mold were aspects of why typha was chosen as a building material. About 300 m^2 of Typha board material was installed, which corresponds to about 15 m^3 of insulation material. Typha components in the form of seed flyers were also mixed into the fiber mixture of the interior and exterior plaster. They helped to increase the cohesiveness and elasticity of the plaster.

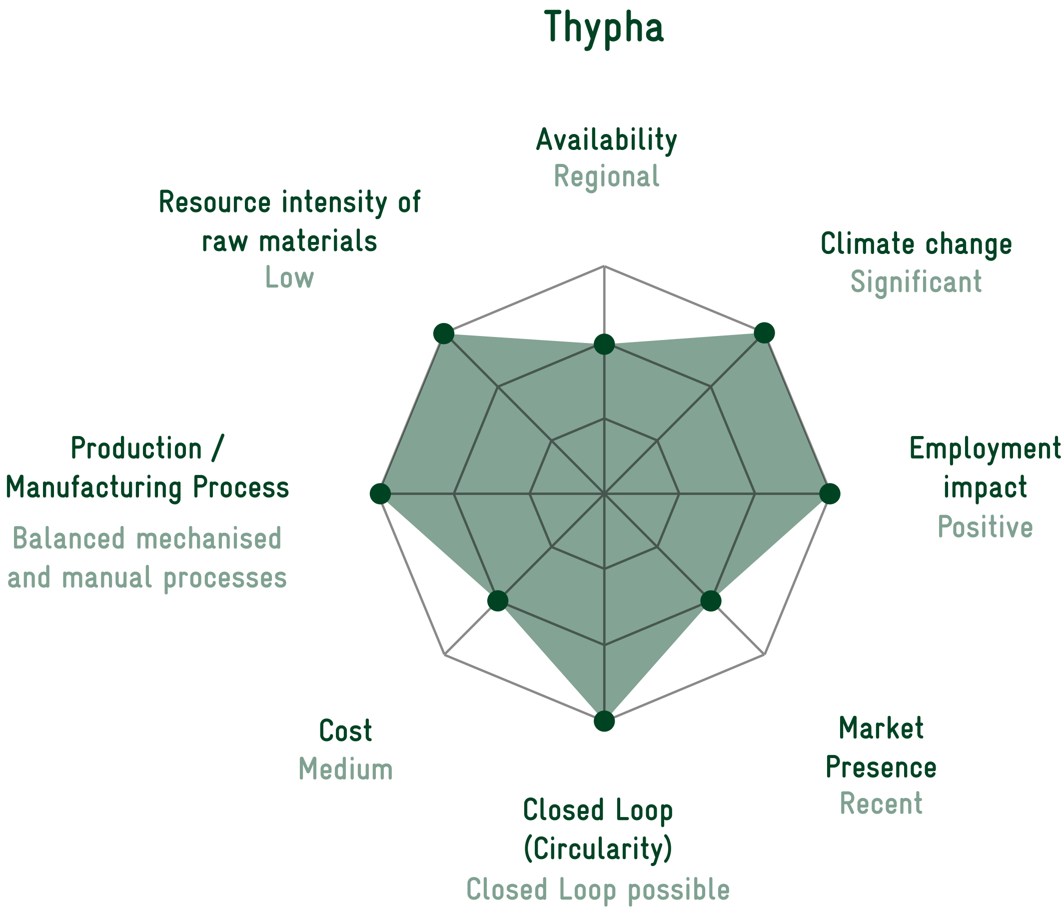
The timber frame renovation and interior insulation was carried out by using the same material. The typha boards are also free of harmful substances. This makes later disposal easier. The natural flame-retardant properties of the material make the use of flame retardants and biocides unnecessary.

Image © Alexandra Fritsch 2003

Image © Alexandra Fritsch 2011

Typha Summary

Typha is distributed worldwide ranging from temperate climate zone to tropical regions, where they can be found in a variety of wetland habitats.



Bamboo

Material Overview

Bamboo is a strong, fast growing resource that has been used structurally for thousands of years in many parts of the world. Today, it has the potential to be an aesthetically pleasing and low-cost alternative to other renewable, and in many regions scarce materials such as timber. Bamboo grows in a "belt" running through tropical, subtropical and temperate climates around the globe. There are more than 1000 species of bamboo in total, broken into two groups: herbaceous and woody. The former tends to be very small-diameter and resemble grasses, while the latter are the more familiar large diameter ones that can be used for construction. Bamboo has a long- and well-established tradition for being used for construction purposes throughout the tropical and sub-tropical regions of the world. With rising global concern on the contribution of building materials to climate change, bamboo is a critical resource which is efficient in sequestering carbon (Swamy, 2011). Bamboo grows naturally on all continents except Europe. It can be found from a latitude of 32° south to 46° north. Generally, bamboos prefer climates with an average annual temperature between 20°C and 30°C, but some kinds of bamboos grow in the fields with temperature as warm as up to 40 to 50 °C. Other kinds can withstand cold weather with temperatures under 0 °C. Bamboos grow mainly at altitudes between 100 and 800 meters but can also be found at sea level and in the mountains above 3000 meters (McClure 1966, Liese 1985).

Due to its ability to grow very quickly and little processing is needed to use bamboo for construction, it is perceived as a quickly developing, and crude economic material. Bamboo can grow in areas that are currently non-productive (e.g., on eroded slopes), and has a high yield since the root structure stays intact after harvesting, generating new shoots. While timber can be harvested every 10 - 20 years, bamboo can be harvested within 3–5 years. The annual productivity biomass of bamboos ranges from 10 to 20 ton/ha/year, whereas wood, for example in Canada, has an average annual biomass production between 21 and 25 ton/ha/year (Heilman et al. 1993 in Yu, 2007). Harvested properly, 10 % of every plant can be taken annually without needing new plants or negatively impacting the original grove.

However, although bamboo has been used for centuries, there is a lack of information especially regarding availability and applications. Policymakers are therefore often hesitant to integrate the plant into their strategies for climate change. Similarly, companies need clear information about bamboo supply before they can begin to integrate the plant into their business plans.

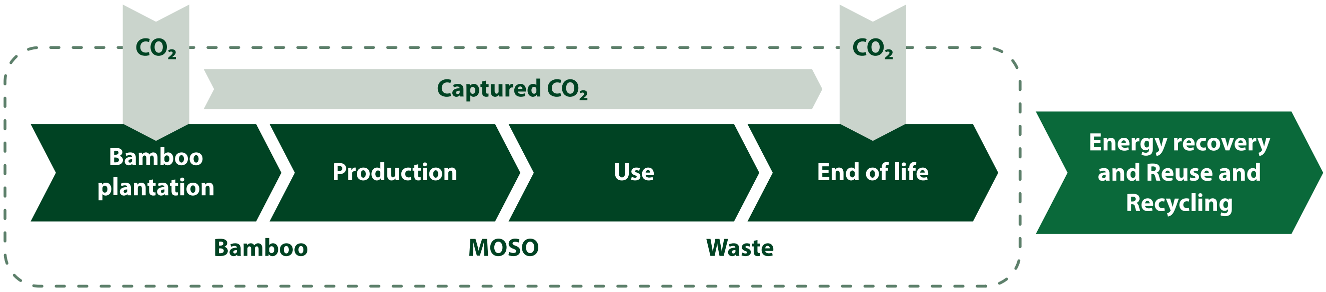


Figure 3 GHG capture and release through bamboo production

GHG and Environmental impacts

As a naturally growing plant, bamboo building elements can sequester around 15 kg CO_2 per m^3 carbon over their lifespan and the plants help protecting the ground from erosion through their rhizome mat, which continues to live after each bamboo harvest (Gu et al., 2019).

If based on best practice technology, bamboo products can be labelled CO_2 neutral or better, however, this depends on the usage and degree of processing and transport distances. Compared to other harvesting processes for timber, less fuel is necessary than by large machinery to harvest trees as bamboo is relatively lightweight because the culms are hollow, and it can be harvested by hand or small chain saws. Energy consumption in processing industrial bamboo products accounts for up to 63% of the carbon footprint of producing bamboo (Van der Lugt, Vogtländer, 2015). Since bamboo processing facilities often use bamboo waste for heat, only the remaining energy required needs to be provided by electricity from the local grid which contributes to the climate impact depending on the source of energy. If the bamboo stem is used locally, the cradle-to-gate carbon footprint lies around 0,20 kg CO_2e/ kg stem but this number can increase up to 1,300 kg CO_2e / kg stem or more when transported by sea (Van der Lugt, Vogtländer, 2015, 2008).

Suitable use for construction

Industrially processed bamboo has shown a high potential for production of composite materials and components which are cost-effective and can be successfully utilised for structural and non-structural applications such as bamboo plywood. It has a high tensile strength and very good weight to strength ratio. The strength-weight ratio of bamboo also supports its use as a highly resilient material against forces created by high velocity winds and earthquakes. Studies showed that the compressive strength for untreated bamboo can be up to 23.80 MPa and treated bamboo up to 36.60 MPa (Modh Doud et al., 2018) with steel showing compressive strengths from 200 MPa and way beyond. If properly treated and industrially processed, components made by bamboo can have a life of 30 to 40 years though natural durability varies according to species and types

of treatments. Bamboo has a high state of flame resistibility due to its high substance of silicate acid. Research into bamboo is still very much in its infancy when compared to, for example, timber. A few bamboo structural design codes in some form exist throughout the world, with the Colombian NSR-10 (2010) being the most detailed. These codes when combined with other research that is freely available provide a relatively good understanding of the axial, bending and shear behaviour of large diameter bamboo culms, in addition to basic guidance on the design of cement rendered bamboo panels and bolted connections. However, aspects still lacking are sufficient material properties for many different species of bamboo and sufficient data and research on the behaviour of connections (Shen et al., 2019).

Considerations for whether bamboo is suitable for a project include the exposure to rain or sources of water, local availability of suitable bamboo species as well as building loads on members and connections (Kaminski, Trujillo Lawrence, 2016). Bamboo must be well protected from both moisture and insect attack. Good detailing such as elevated column and wall bases, a large overhang, good drip details and periodic painting of the walls will help against rot, while boron appears to be by far the most appropriate and best chemical to control insect attack. Bamboo exposed to the elements, however it is treated or maintained, is expected to deteriorate.

Figure 4 Bamboo processing

Production, process and employment effects

Among the numerous industrial utilizations of bamboo, bamboo plywood is nowadays one of the most typical and often found industrial products of bamboo. Like many other industrial bamboo board-like products, bamboo plywood is processed similar to the process of engineered wood products (see Figure 4). In the processing, bamboo canes will be split into strips at first and then cut into square sections so they can be glued and pressed together into a multilevel board. Plywood bamboo is often used as a substitute for wood products like floorboards, or bottom boards and forming boards for concrete (Zhang 2001). Compared to normal wood floorboards, plywood bamboo has a slightly harder surface.

There is great scope to increase productivity from existing bamboo forests by regular silvi-cultural practices, such as water conservation, soil working and maintenance of health and hygiene of clumps. There is potential to raise bamboo plantations as a business venture in forests and farms. Bamboo production has not received adequate attention either in the forestry or the farm sector, in spite of increasing shortages in its availability. Bamboo hence holds opportunities for the establishment of local, regional industries involving varying skillsets especially for the low-income sector, as primarily low-skilled labour is required for harvesting and processing. Especially for rural areas, bamboo holds potential for employment generation, where it is often harvested by local communities (Rana et al, 2010; P.M. Mathew, 1998).

Circularity

As bamboo is a natural material, it is possible to be shredded and returned to the material cycle after end of life by composting. However, Bamboo is high in lignin, a component that takes a long time to decompose. Further, despite the environmental benefits bamboo has on construction, bamboo is often sliced into pieces and glued together while working with. Presently no specific standard is stated for its construction or gluing together, and glue contains formaldehyde which can be harmful to the environment (Kennan, 2015). Currently, it is assumed that 90% of the bamboo products are incinerated in an electrical power plant and 10% end up in landfills (Western Europe) (ibid).

Next to shredding and composting, bamboo parts could also be reused as whole. However, this depends on whether glue and additives have been used and can be dismantled. The most common treatment for bamboo is based on boron salts which are effective against borers, termites and fungi (except soft rot fungi). These boron salts are not toxic and dissolved in water. After treatment, the water evaporates leaving the salts inside the bamboo.

Case Study:

Cerchas – La Ceiba

Location: Chiapas, Mexico

Architects: Lucila Aguila

Urban Typology: Multi-use building, camping site dormitory

Year of construction: 2016

Materials: Earth, bamboo

Costs: not disclosed

The building is part of La Ceiba, a social infrastructure project developed for Uumbal, an agroforestry company located in the southeast of Mexico. The project introduces materials and design strategies with low environmental impact and high aesthetic quality that meet the needs of safety and operation. The project for the camp dormitory is configured by means of a bamboo structure, whose constructive logic is based on rigid frames made up of two types of trusses; one vertical located in the centre and two inclined to the sides. The trusses follow a construction process to be manufactured on site, from reference points on the ground that make the mould or template for the reproduction of each of the trusses, in a more efficient way in time and form.

Natural materials such as earth and bamboo are mixed with conventional materials in an attractive and functional design. It was aimed to use as little concrete as possible, especially in the foundation, with the overall aim to use local techniques with natural materials (such as rammed earth walls) or other sustainable options.

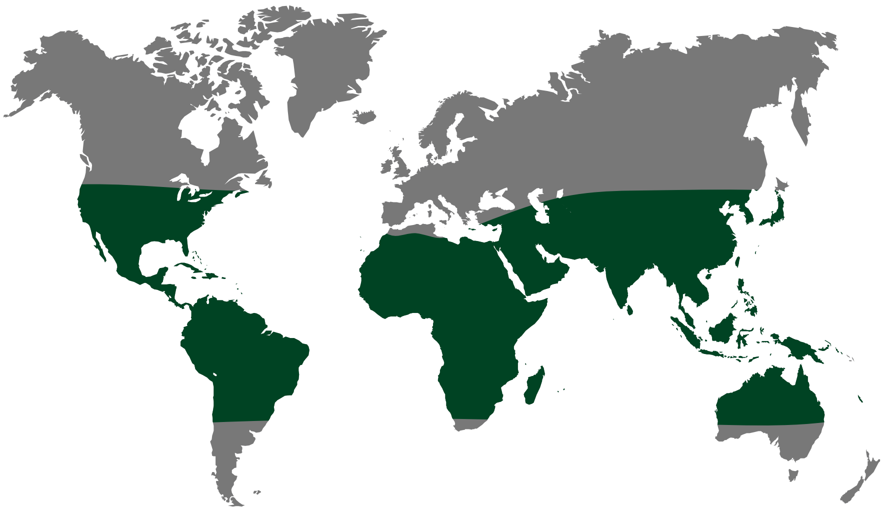
The proposal promotes dry construction and the use of resources that can be useful beyond the life of the building. The design responds to a bioclimatic strategy for warm-humid temperatures, and the constructions are strategically oriented to benefit from the winds and the position of the sun. In addition, they have a bamboo roof and vegetable cover that provide shade, comfort and harmony, and respect the dignity of the work of the Mexican countryside. This building integrates a cross ventilation design, wattle and daub earthen walls and green roofs for thermal insulation.

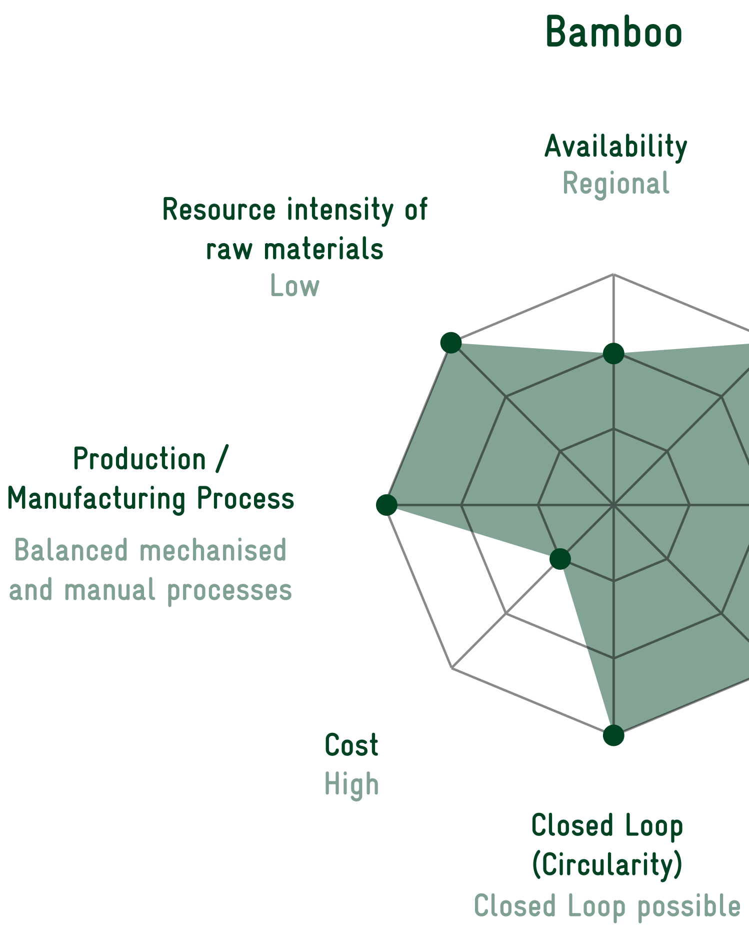
Bamboo is a locally grown material that exists in abundance in the south-east of Mexico. Bamboo was used rarely since it was an unknown material for construction, but in recent years, the material has been gaining interest since it is cheap, is locally available, strong and regenerates easily. Highly qualified labourers are not required as bamboo is very easy to work with and only simple tools are needed, making it especially suitable for use in rural communities without need for industrial processes.

Images © Lulila Aguilar

Bamboo Summary

Bamboo grows in a "belt" running through tropical, subtropical and temperate climates around the globe, and can be found from a latitude of 32° south to 46° north. It grows naturally in all the continents except Europe. Generally, bamboos prefer the tropical or sub-tropical climates with an average annual temperature between 20°C and 30°C, but some kinds of bamboos grow in the fields with temperature as warm as up to 40-50 °C and other kinds of them can withstand the cold weather with temperatures under 0°C.





Mass Timber

Material Overview

Mass timber is a term used to describe a family of engineered wood products of large section size. The term is generally applied to thick panel products for wall, floor and roof construction but can also include large section glued- or block-laminated linear elements (GLULAM, CLT). There has been a significant increase of interest in these products and building systems due to their technical capabilities, cost-competitiveness and environmental properties (Harte, 2017). In the construction of multifamily residential and commercial multi-storey buildings, cross-laminated timber (CLT) is the most widely used mass timber product (Brandner et al., 2016; Harte, 2017).

Unlike concrete and steel, which emit CO_2 when produced, trees used to make mass timber products naturally absorb and store CO_2 as they grow. Increasing the amount of wood used in buildings, as a substitute for more carbon intensive materials, has the potential to decrease total emissions from the building sector (Hill, 2019). However, it is worth noting that timber can only be sustainable when sourced locally and from sustainable managed forests. In sustainably managed forests, new trees are regenerated to replace trees that are harvested so that there is no net loss of forest carbon (Gustavsson et al., 2017). Therefore, the regional availability and value chains need to be considered when sourcing timber. Sustainable timber must be planted and harvested in very specific ways in order to retain its eco-friendly status. Different forestry certification schemes can aid users of wood and wooden products in knowing the source of the wood for a project.

Timber and wood-based products are becoming increasingly important structural materials for sustainable construction globally. The introduction of mass timber products with excellent load carrying characteristics allows timber to be used in larger, more complex structures. CLT panel products have developed to the stage where they can be considered as economic and more sustainable alternatives to traditional materials. Timber is considered a natural, renewable resource, and extraction and manufacturing of timber products requires a very low amount of energy relative to more conventional structural materials used in construction. In addition to sustainability benefits, one of the primary advantages of CLT construction is offsite prefabrication allowing for high-quality certified production, independent of weather conditions. As holes and notches in panels can be pre-cut prior to arrival to site and assembling methods are straightforward, construction and project delivery times are improved, and costs reduced. Prefabricated CLT building systems are easily erected in a low-dust, low-noise assembly with minimal site waste.

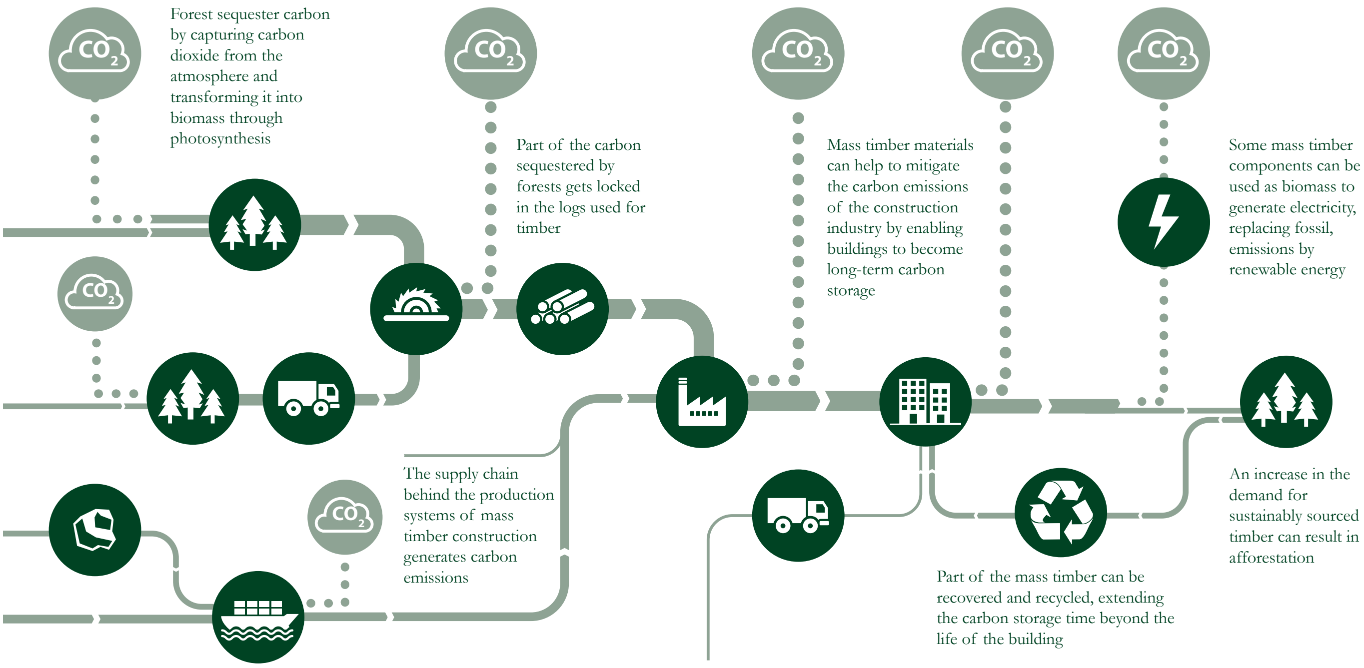


Figure 5: LCA of Mass Timbe. Source: Monash University

GHG and Environmental impacts

Timber building elements sequester carbon over their lifespan. Dry wood is made up of about 50% carbon by weight and so mass timber buildings store considerable amounts of carbon, approx. 600 kg/CO_2e/m^3, dependent on wood type (CINARK, 2021). During the lifespan of the building, several forest rotations can take place with further carbon sequestration in the forest. Additional benefits accrue due to the substitution effect, which is the avoidance of emissions associated with replacing more energy demanding materials with wood products (Sathre & O'Connor, 2010).

Several studies have been carried out to quantify the environmental benefit of construction in timber using life cycle analysis procedures. At the global scale, it is estimated that about 4.7 to 10.3 GtCO_2 per year could be saved by substituting wood for steel and concrete in building and bridge construction (Himes, Busby, 2020). In a more recent study on the potential for timber buildings to serve as a climate solution, Churkina et al. (2020) highlighted that construction of wood building for new urban dwellers could provide long-term carbon storage of 0.01 – 0.68GtC/year in the buildings themselves. The variation in estimates demonstrates the inherent complexity of these studies and emphasizes the importance of consistent and systematic methods so that results can be compared. According to a meta-analysis by Himes and Busby (2020), substituting conventional building materials with mass timber in mid-sized urban construction reduces construction phase emissions by an average 216 kgCO_2e/m^2 of floor area.

Suitable use for construction

Many buildings have been constructed using timber across a range of building types mostly as low-rise construction. Until recently, wood was primarily used in the construction of single family or small multi-unit wood framed buildings (Brandner et al., 2016), limiting its potential in urban areas where new, low-carbon construction should prioritize larger mid-rise buildings. However, the development of mass timber technology in recent decades has paved the way for constructing mid- and high-rise buildings with wood to meet the built environment demands of a rapidly growing global urban population (Brandner et al., 2016; Harte, 2017). CLT timber structures of up to 85m or 24 storeys have already been constructed in European countries such as Norway, Sweden Germany or Austria. The feasibility of building a timber structure up to 30 storeys tall using CLT has been investigated and a number of engineers around the world are currently investigating the use of CLT for even taller structures. One great advantage of a CLT structure is the safety and efficiency during the construction process brought about by easier handling and higher-level prefabrication compared with alternative materials. There is also less waste generation and noise pollution during construction (Liang et al. 2019).

Production, process and employment effects

Depending on the species, timber can be harvested every 10-20 years or even after longer periods. After harvesting, logs are stored in a clearing or in the forest until they are processed at the sawmill. This also allows some of the water content to evaporate, reducing the weight of the log, which will result in lowering the cost of transporting and handling. The trees are usually cut into smaller lengths on-site and then picked up by a timber lorry, which transports the timber to a processing site.

After turning trees into timber through saw milling, also referred to as primary processing, the market value of timber can be further increased through manufacturing sawn timber products – called secondary processing. After primary processing, the raw materials are then transported to produce engineered woods manufacturing such as GLULAM or CLT. To manufacture engineered woods, skilled to highly skilled labour is necessary as well as heavy machinery.

As timber has been used for centuries as building material, it has an established market presence in many regions worldwide. Start-ups exist for very specific applications of timber for construction such as glue less joints. However, most of the market is already established, primarily in regions with an abundance of forests.

Circularity

As wood is a natural material, it can potentially be shredded and returned to the material cycle after end of life by composting. However, as wood can take a long time to decompose and is often treated or glued together, there is little experience with the dismantling, reusing and recycling of (larger) wooden structures and wood are often used for thermal energy generation. In planning, it is therefore important to develop solutions for the dismantling of tomorrow today so as not to generate new problems. Ease of disassembly allows for reuse of the material and a more resource-efficient product life cycle.

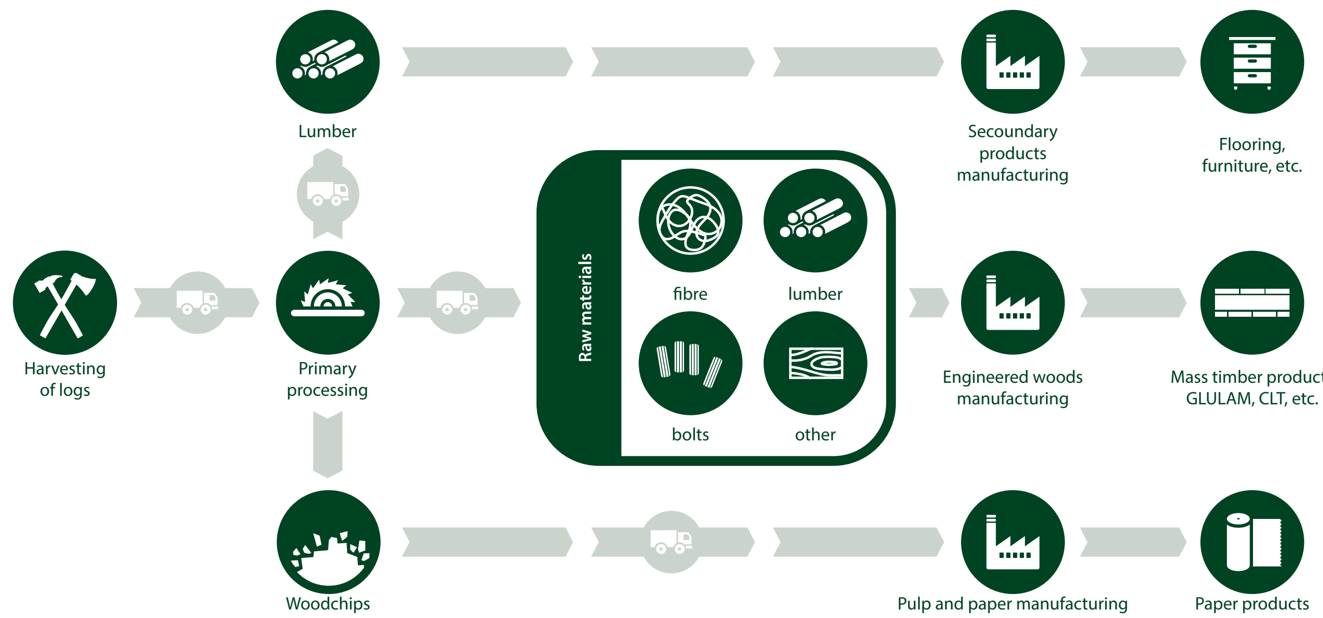


Figure 6 Value chain for processing timer

Case Study:

Hawaii Preparatory Academy Energy Laboratory

Location: Kamuela, Hawaii

Architects: Flansburgh Architects

Urban Typology: High school science building

Year of construction: 2010

Materials: Wood frame

Costs: not disclosed

The Hawaii Preparatory Academy Energy Laboratory has been designed by Flansburgh Architects and Buro Happold using only renewable resources. All the wood in the building is Forest Stewardship Council certified or from salvaged sources. The walls of the building are made of wood framing with batt insulation and fiber cement board and batten siding. The roof is made of wood with rigid foam insulation and corrugated aluminium-zinc alloy coated sheet steel panels.

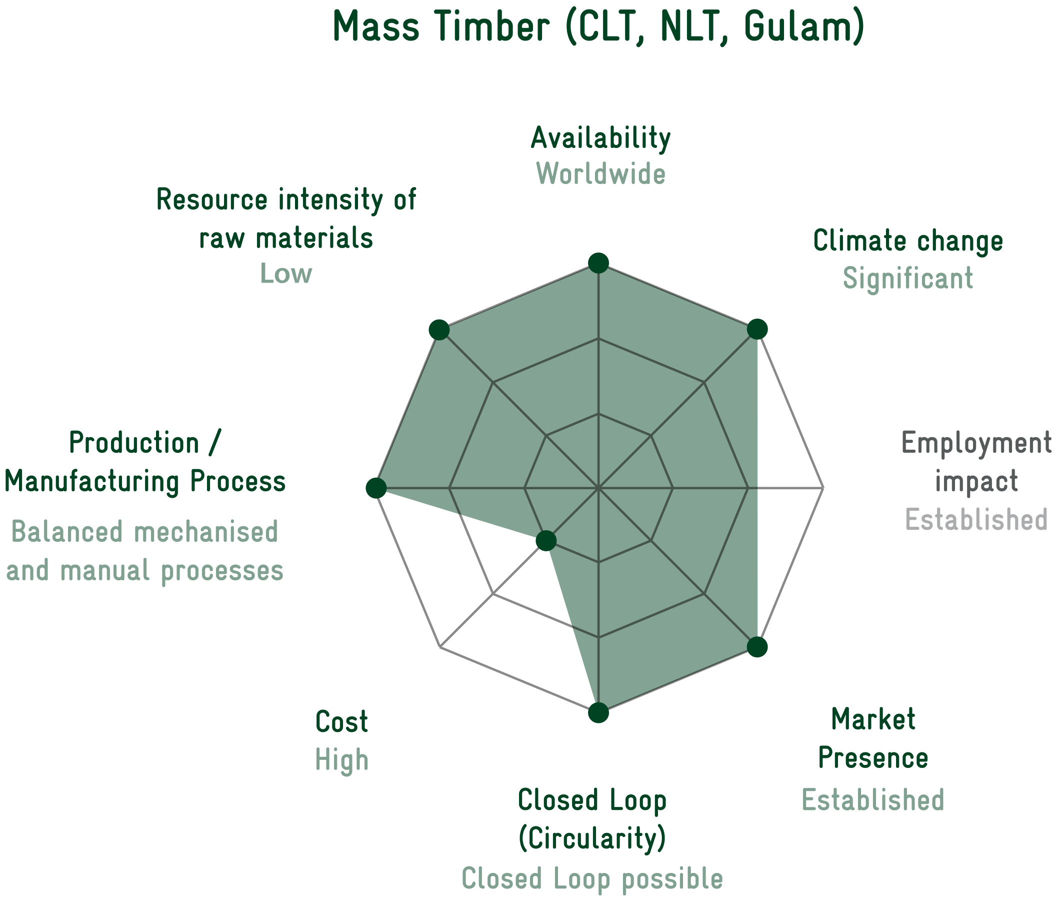
Conceived as a building dedicated to the study of alternative energy, the new Energy Lab at Hawaii Preparatory Academy functions as a zero-net-energy, fully sustainable building. The high school science building with 6,100 square feet is a Living Building Challenge (LBC) candidate currently in its audit period. The LBC was developed by the Cascadia Region Green Building Council and is the most ambitious performance-based standard for green buildings. Its requirements include net zero water, net zero energy and the exclusion of Red List materials, such as PVC, formaldehyde, lead and halogenated flame retardants, and other chemicals and materials considered harmful to humans and the environment.

Furthermore, the LBC set transportation distance requirements for all building materials. Heavy density materials must be transported from a distance no greater than 1,000 miles, medium density materials no greater than 3,000 miles, and light-density materials no greater than 5,000 miles.

Images © Flansburgh Architects 2010

Mass Timber Summary

Forests tend to fall into one of three types based on their location: boreal, temperate, and tropical. Boreal forests are located the farthest north, temperate forests grow in the mid-latitudes, and tropical forests are found closer to the equator. Countries with the largest forested area include Russia, Canada, Brazil, China, and the United States.



Straw Bale

Material Overview

Straw bale construction is a wall system using stacked bales of straw that are covered with plaster or other finish. Straw bale buildings were first constructed in the USA in the late 1800's, when baling machines were invented (Jones, 2002). The pioneers in Nebraska started using bales of meadow hay to build everything from churches to houses (Steen, Steen, Eisenberg, 1994). The oldest recorded European straw bale house was built in France in 1921 (Atkinson, 2008). When straw bale construction was rediscovered in the 1980s, it was further developed, including considerable testing and research regarding structural performance (under vertical and lateral loads), moisture, fire resistance, and thermal properties. Straw bale buildings are durable, safe, energy and resource efficient, and have proven affordable compared with predominant building systems in countries of the Global South. When detailed properly, they are highly resistant to earthquakes. While the use of straw is still largely niche, it has grown significantly around the world in recent years, supported by new research, construction innovations and building codes of practice (Walker, Thomson, Maskell, 2020).

Straw is produced annually as an agricultural by-product of rice, wheat and barley cultivation at elevations up to 3000 meters. It is normally used as a low-grade animal feed, and sometimes for roof thatch (Builders without borders, 2015). Straw bale construction is thought to be very sustainable as it represents a low carbon footprint while using locally sourced natural materials which cut down on transportation impacts and creates very little waste. As straw is a waste, or agricultural by-product, enough straw is currently produced every year in North America to meet most residential building needs. The same is true worldwide, since grain farming is common across most cultures and regions. This makes straw bales a renewable resource for construction purposes. As straw is currently produced surplus to requirements in many countries of the Global South and often burned illegally and uncontrolled, straw bale construction has great potential to make use of this waste material and reduce lung and chest diseases of the population stemming from illegal straw burning (Garras, Allam, Dessuky, 2009).

GHG and Environmental Impacts

Straw can be produced from different plants, including wheat, rye, barley, and rice. Each and every cereal gives a different final product in terms of thermal resistance and durability. From

Building a straw-bale house, Designed by Carina Rose. Author Colin Rose
https://commons.wikimedia.org/wiki/File:Straw_Bale_House06.jpg

an environmental point of view, the ideal scenario would be to collect straw from a field close to the construction site, thereby ensuring a short-chain production cycle.

Straw stores sixty times more carbon than is used to grow, bale and transport to building sites in the same region. A straw bale is made up of approximately 40% carbon by weight. It naturally sequesters carbon both in grain stalk itself and by storing carbon into the soil. The embodied energy of straw construction depends on the type of construction, processing and the transport to construction site. Therefore, no general value can reflect the embodied carbon of straw buildings, however, studies showed ranges between 0,0014 MJ/kg and 0,4 MJ/kg straw (various values depending on analysis type with different parameter). The usage of locally available straw can further reduce embodied carbon, carbon emissions, energy and transportation cost, as well as support the local economy.

Once constructed, the airtight straw layer is long-lasting and fire-resistant. The straw is packed densely, and fire tests show that, without oxygen to feed the fire, it can withstand flames at 1,050°C for over two hours. The straw insulation is packed densely enough to keep warm air in yet permeable enough for humidity to escape, creating a healthy and comfortable indoor climate, with estimates suggesting a saving of 1 t CO_2/year on heating and cooling. Low straw yield years due to variable weather conditions, rate of uptake of organic methods and resulting availability would increase the emissions impact of transportation of straw on a project-by-project basis, and certainly influence cost-based decisions.

Suitable use for construction

There is a wide range of technical opportunities with straw building systems. The essential characteristics of the construction systems can be summarised by grouping them into two broad categories (Mutani et al., 2020): Load bearing, where straw bales ensure both structural support and thermal insulation, and in-fill, where straw bales are used as insulation only. With the former, together with the plaster that covers them and all the materials that make up the stratigraphic package, the straw bales transfer the loads from the roof and from the horizontal elements to the foundations. The cost-effectiveness and speed of execution are offset by the reduced bearing capacity of the walls. For the latter, straw bales are used as an insulation filler between supporting structures, which are satisfying the structural function requirements of the building without structural support from the straw bales (Jones, 2002).

When built with an additional structural frame, straw bale houses can be constructed with multiple stories. Studies have shown that straw bale walls have a good ability to carry loads and are capable to withstand loads of multi-story building up to three stories with help of structural frameworks (Adam, Ali, 2015). The nature of straw bales is flexible so that the plastered bale assembly can be designed to provide lateral and shear support for wind and seismic loads (Nadav, 1993; Adam, Ali, 2015). Properly built and maintained, straw buildings can have a useful lifespan of at least 100 years. The straw bale thickness in a wall is the main factor that will influence the thermal and energy performance of a straw bale building. Whole straw bales usually measure around 1 × 0.5 × 0.4 m and lead to finished wall thickness of 0.45 to 0.55 m. Thermal conductivity of straw is around 0.07/0.09 $W/(m^2 \cdot K)$, which is fair compared to expanded polystyrene (0.04 $W/m^2 \cdot K$). A finished wall of around 25 cm has similar thermal resistance as 10 cm of expanded polystyrene (Gonzales, 2015).

Two significant challenges related to straw-bale construction are moisture and mould. Buildings need to be protected from rain and water leakages into the walls. Compressed straw might expand when exposed to moisture which can cause cracking and more moisture to infiltrate the walls. This can lead to mould releasing toxic spores into the air and makes weather proofing essential for straw bale construction. The best way to avoid sustained high moisture concentrations lies in securing that the bales are able to transpire any accumulated moisture back into the environment. Straw bale construction may not be well-suited for consistently high-humidity climates.

Production, process and employment effects

Straw bale is considered a low-cost material for several reasons: It is readily available, can be obtained from both near and far sources and is a lightweight material so can be transported economically viable. The building method is straightforward and people without previous building experience can participate in the design and construction process, thereby saving on labour costs. Straw is a by-product or waste material from agricultural uses of grain, rice and wheat and usually used after agricultural uses such as food production or animal feed stock. However, straw is also used as a source for heat production when burned for heat or electric power.

Examples from Nepal show (see case study) that straw bale constructions entail a positive impact on local communities and gender equity as mainly women were trained into leadership roles for lime stabilized plastering. Projects of straw bale construction further enhanced community capacity building through increasing skills and income. The project has shown that trainings and use of local labour are an important factor, to empower communities to build durably with straw and lime, allowing to maintain their buildings and implement future projects autonomously (Re-Alliance, 2021).

Circularity

When straw buildings reach their end-of-life and need to be demolished, its walls can decompose into the soil as the material is completely biodegradable. It is important to note, as straw is an organic material, the finishes on straw walls must also be composed of an organic material to allow the walls to exchange air between the indoors and outdoors. Therefore, a mixture of clay, sand, and straw is generally used but lime is a viable option. As straw is a mostly unprocessed material, it is also a potential food source for microorganisms like fungi and bacteria. Under the right conditions this can be a primary way that the straw is decomposed in a process of composting. However, if used with a plaster or other finish, straw needs to be sorted or disassembled at end-of life.

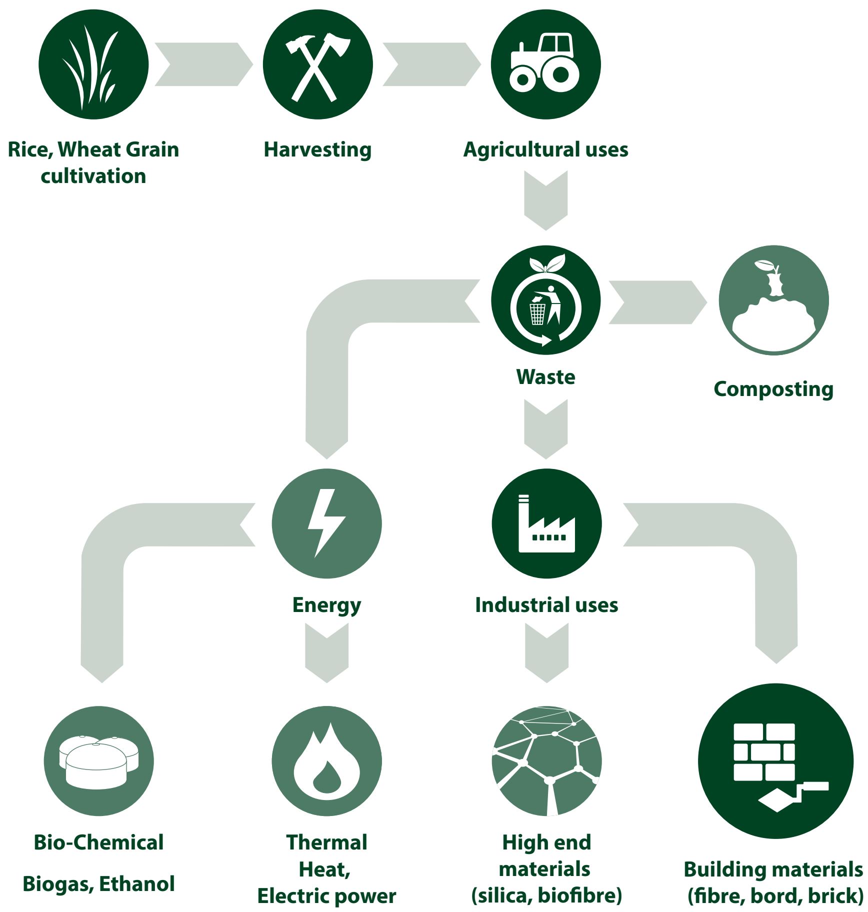


Figure 7 Straw bale as an agricultural waste material

Case Study:

Paral Ko Ghar – Nepal's First Straw Bale House

Location: Khorang, Nepal

Architects/Developers: Martin Hammer, Kevin Rohan Memorial Eco Foundation/Builders without Borders

Urban Typology: Single residential building

Year of construction: 2018-2019

Materials: Strawbales, straw clay, bamboo, metal sheets

In 2018, Builders Without Borders and the Kevin Rohan Memorial Eco Foundation built the first straw bale house in Nepal. The building was part of programme for sustainable rebuilding in post-earthquake Nepal by an international network of ecological builders who advocate the use of straw, earth and other local, affordable materials in construction.

The design of the one storey building uses local materials such as stone, bamboo, straw, wood, sand and clay-soil. The straw bale walls are highly insulating, providing high thermal comfort both in winter and summer. The design can get applied in many regions of Nepal, at altitudes 500 to 3000 meters wherever rice, wheat, or barley are grown, and bamboo is available.

The house accommodates 3-6 people and can be built in 4 phases. It consists of two rooms, a kitchen, a multi-purpose room, and a veranda with a total floor area including veranda is 65 m^2. To build the walls, loose straw was compacted into bales using a steel mold and a farm jack and then placed on a cemented stone foundation. The bales were then held in place with external bamboo pins. A simple metal roof protects the house along with the earthen plaster. One straw bale weighs approximately 4 kg and takes around 15 minutes to be produced by two people.

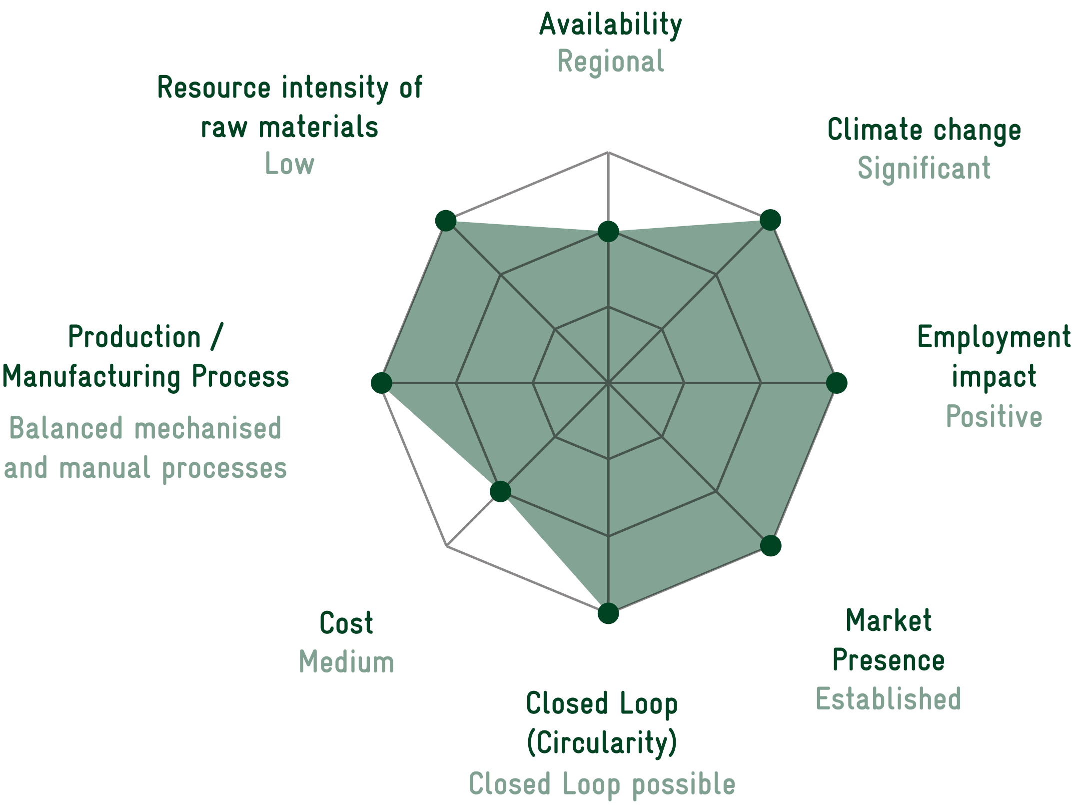
Using local labour, materials and sharing skills with local people who worked alongside and in leadership roles meant this durable, safe, regenerative building was easily affordable. The estimated building costs are thought to be about half of the cost of conventional earthquake resistant buildings. The addition of lime-stabilised soil render has given the building a durable, breathable finish and trained especially local women to continue the maintenance of this building and construction of other buildings.

Images © Builders without borders 2019

Straw bale Summary

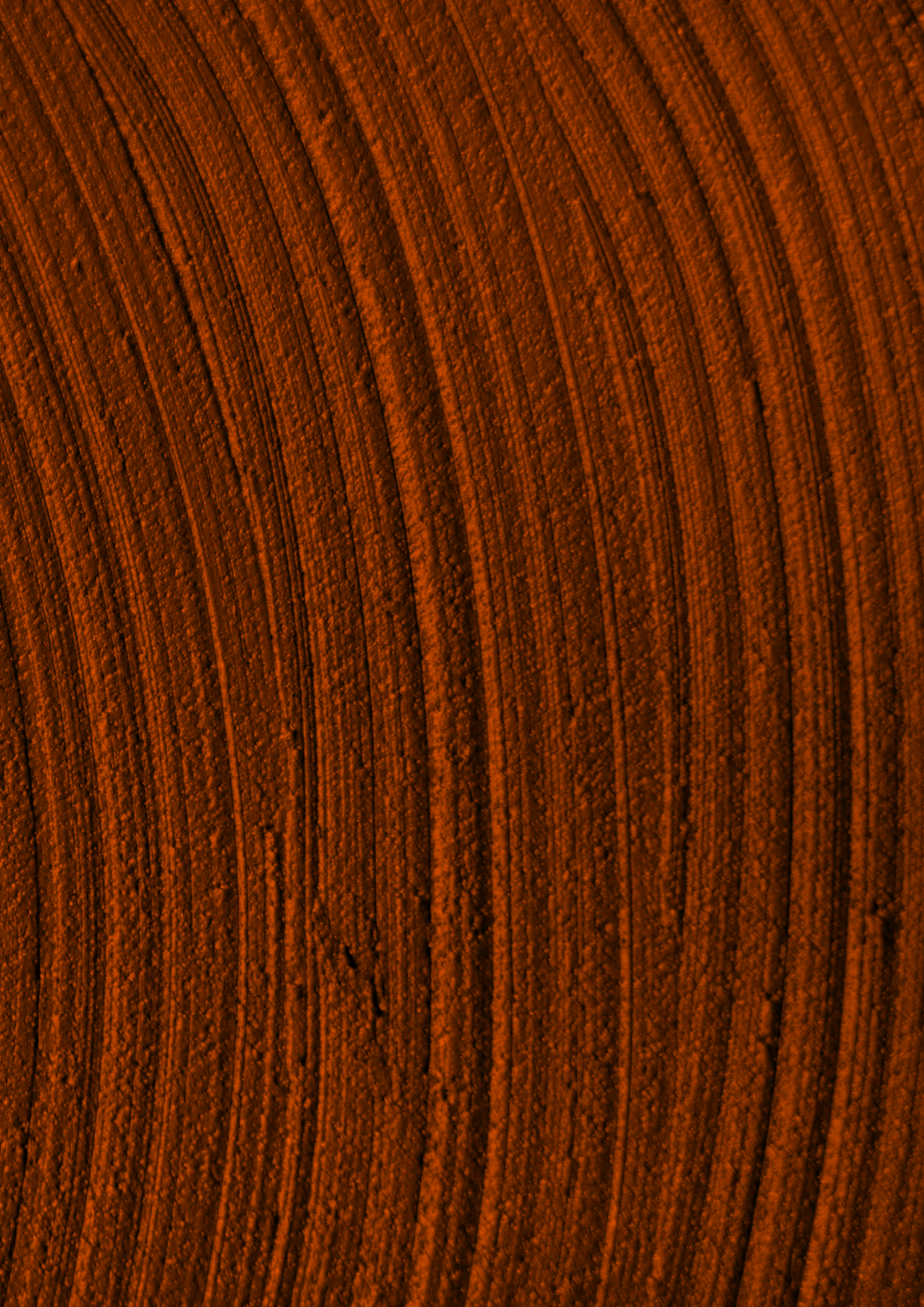
Agricultural plants such as cereals (i.e. wheat, rice, barley, oats, rye), corn, cotton, etc. are globally grown for the crop. China, India and the USA appear to be at the present the major producing countries of straw residues (mainly wheat and rice straw).

(Rice) Straw Bale



3.3 Clay and brick

The following section shows the material group of clay and brick, including unfired clay and rammed earth. Among the other basic building materials, especially unfired clay bricks (adobe) can be appraised as an energy efficient choice. With clay being a widely available resource especially in countries of the Global South and less energy intense processing, this organic material holds great potential for CO_2 mitigation in sustainable construction. Similarly, rammed earth constructions can be highly sustainable as it has a high thermal mass and only a 40th of the carbon footprint of concrete.



Unfired Bricks

Material Overview

Unfired clay brickwork, also known as earth masonry, is constructed using earth materials (possibly with some additives). Earth masonry is not "fired" in kilns like conventional bricks, but the masonry units are air dried after manufacture to reduce shrinkage and improve strength. Air dried clay bricks are one of the earliest forms of unfired clay bricks, dating back to 7000 BCE, when the bricks used to be in the form of sun-dried mud blocks. Since then, a lot of modifications have been done in the composition of bricks and in brick making procedures. As a result, now-a-days, bricks are mostly made of clay and sand mixed in suitable proportion, to which binder is added (Murmu, Patel, 2018). There are many regional variations of unfired clay bricks around the world that reflect available materials, climate and culture. With many variations, unfired clay bricks are not bound to certain geographic areas but can be produced in most climates and regions of the world. Studies found that under the right circumstances, brick structures can have a lifespan of 500 years or more (Bown, 2007). There is an observable increase in the researched use of compressed earth masonry units. These units are increasingly being seen as industrialized materials, and no longer considered as only appropriate or applicable to traditional approaches for self-construction (Cid-Falceto et al., 2012).

Unfired clay bricks can be classified as traditional or modern bricks, where traditional clay units such as cob and mudbricks are bricks made manually without using any advanced technique. Modern sun-dried clay units, also known as compressed earth blocks (CEB) are fabricated with precise tolerances with the help of extrusions or pressing systems which leads to improving their properties, and hence their quality. Unfired adobe bricks are perceived as eco-friendly and energy-efficient construction materials that can achieve great carbon savings. Furthermore, extraction of the raw material (earth) has minimal environmental impacts which is particularly important in regions where clay as a raw material is locally abundant (Christoforou et al., 2016).

Regarding risk areas and resilience, it is worth mentioning that unfired clay systems stand little chance in flooding situations. Therefore, clay systems exposed to the elements demand far higher expectations in terms of robustness compared to those used for internal walls or other protected environments.

GHG and Environmental Impacts

As a naturally abundant material, the embodied energy of clay is considerably low. The energy content of clay-based material mainly consists of the energy spent in some primary crushing and transport which means that if clay soil is produced locally, these energy usages are almost negligible. The GHG emissions depend largely on the stabilisers added to the earth bricks as well as transport processes to site. Compared to fired clay bricks with around 560 kg CO_2eq/m^3, unfired earth bricks emit only 95 kg CO_2eq/m^3. The values show the significant impact clay-based materials could have especially when replacing fired clay bricks. However, the CO_2 balance depends on the additives and stabilizing agents of the clay bricks. For bricks with a proportion of 5 - 10% of lime or cement, the CO_2 emissions will be significantly higher as it is estimated that per 1 kg of cement produced, 0.5 - 0.9 kg of CO_2 emissions are evolved (Fayomi et al. 2019).

Suitable use for construction

Unfired clay masonry construction can be used for both non-loadbearing and loadbearing walls such as partitions (Brick Development Association, 2009). However, the clay bricks need to resist shrinkage, cracking, freezing/thawing and erosion due to directly or indirectly effect of water. In addition, if performances such as fire resistance and sound insulation are required, additional specifications are usually imposed, such as sufficient durability to resist local exposure conditions in order to maintain the structural and operational integrity of the building (Oti, 2010). Unfired clay bricks are expected to perform favourably in most building applications where fired bricks are currently being used for masonry wall construction. Enhanced compressive strength can be achieved through additives (soil stabilization) such as fly ash, lime, cement, furnace slag or other (Kinuthia & Oti, 2012). Unfired clay masonry has a compressive strength similar to aircrete blockwork, around 1-4 N/mm^2, although this can vary depending on the clay content and method of block manufacturing.

Unfired clay bricks provide advantages over fired clay bricks because of their simplicity and low cost, good thermal and acoustic properties. Assessment of the compressive strength of unfired clay brickwork showed to be more complex than for fired clay bricks and no single strength value can be assigned. The strength of unfired brickwork is dependent on the material properties, the dimensions of the wall and the water content. The material property that influences the masonry strength more than any other is the clay content in the masonry units. Traditional forms of unfired clay bricks (cob blocks, adobe and mudbricks) are generally made by hand and as a result, have variable dimensions and other properties. Traditional earth masonry has thick walls (often over 300 mm thick) as the mortar provides low bond strength and the thick walls have sufficient mass to keep themselves stable against lateral loads in dwellings. Increasing the wall thickness will open the possibility for structural use of unfired brickwork.

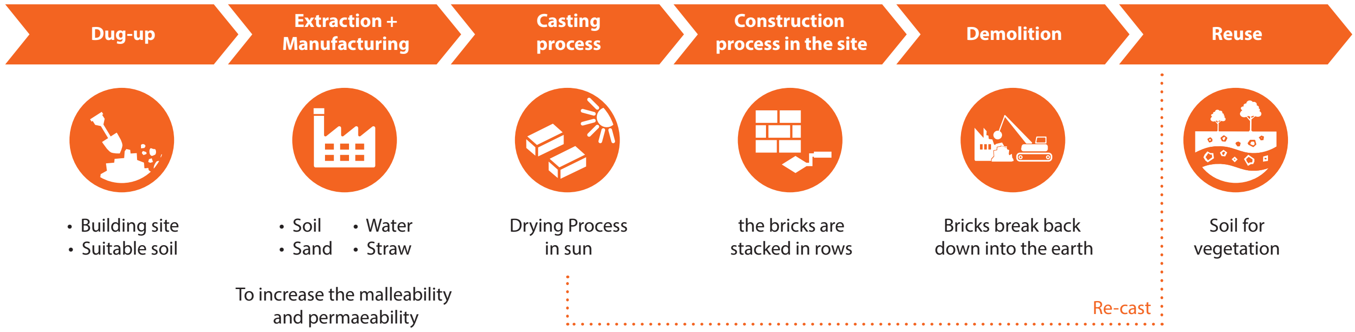


Figure 8 Production process unfired clay bricks

Production, process and employment effects

Unfired clay bricks can be cast on-site easily and quickly, thus eliminating or reducing the need for raw material transportation. If locals cast bricks themselves, less energy-intensive techniques have both the advantage of reducing transport-related energy and CO_2 emissions together with creating employment possibilities.

Clay bricks are being made using suitable soil, additives such as straw, sand or cement and water. The soil is sieved, mixed and rammed or precast into compressed earth blocks. The bricks are then going through a drying process for various days, depending on the additives and level of humidity. The moisture content for raw material going into the pressing machine is typically kept at around 10 – 13%. Once moulded, unfired bricks are left to dry in controlled conditions, rather than fired, which significantly reduces the overall embodied energy. When delivered to site, unfired clay is not as resistant to damage as fired clay, hence care should be taken with site storage, most importantly ensuring bricks are kept dry, including protection from rising moisture from the ground or very high humidity levels.

Since the processing of clay brickwork does not require a lot of technical skills, it can be practiced by the local workforce, creating employment. Raw earth processing requires good knowledge and understanding of soil types in order to obtain the appropriate soil mixture. For compressed earth blocks, it is important to train people on how to operate and adjust the machine to maintain quality control of the blocks. With 6 – 8 people, between 1,500 and 2,000 blocks can be produced per day using a single hydraulic block machine (Bowen, 2017). Building with raw earth, however, does not require specialised manpower, which allows anyone to build a house with resource to simple tools.

Circularity

At the end of a building's life the bricks can be re-used, or clay material can be returned to the ground without interfering with the environment (Morton, 2008). In the demolition phase, buildings constructed from sun-dried bricks can get disassembled using manual tools like axes. Depending on whether additives such a cement or lime were used, the bricks can degrade back into nature as soil (Dabaieh et al., 2020). However, cement is often used as an additive to stabilise unfired earth bricks. In this case, it would be possible to reuse the bricks if they can be recovered as a whole and if no finishing was used. However, recycling bricks does not work, if cement is added to the soil mixture.

Case Study:

Vaulted brick primary school, Mali

Location: Wadouba, Mali

Architects: LEVS Arkitekten

Urban Typology: Primary School

Year of construction: 2018 (Construction time 5 months)

Materials: Compressed earth blocks

Costs: 45,000 EUR

CO_2 Balance: Reduction of 99% of energy consumption compared to cement blocks

Dutch Firm Levs Arkitekten used unfired clay bricks from local mines to build a primary school with a barrel-vaulted structure. The compressed clay bricks were used to build walls, floors and roofing. The usage of these blocks of compressed earth leads to a smooth integration of the school into its surrounding environment.

The pressed stones withstand such a great pressure that load-bearing walls can be built from them, even with several floors. Dutch building has a long history of making brick facades and patterns. The size and quality as well as other properties of the stone used influence the final dimensions of a design. In the case of the pressed stone, stone can be used as a decorative element, for example by making patterns and reliefs with it. As a result, the designs have acquired an increasing architectural sophistication in which Malian and Dutch traditions are brought together in a modern way.

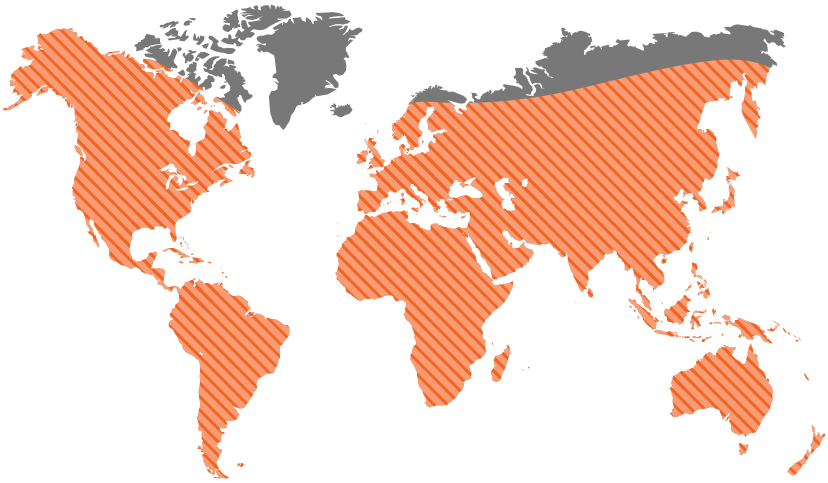
The school complex is made up of several blocks, but the main teaching areas are located in one single-storey classroom building. Levs Architecten positioned three identically sized classrooms in a row, paired with sheltered verandas on each side for the students to take a rest in between classes. Through the use of a newly developed hydraulic-compressed earth block, the building withstands the climate of both hot sunlight and heavy rainfall. In order to achieve a waterproof layer, the roof has been covered by a thin film of red earth, mixed with 6% cement.

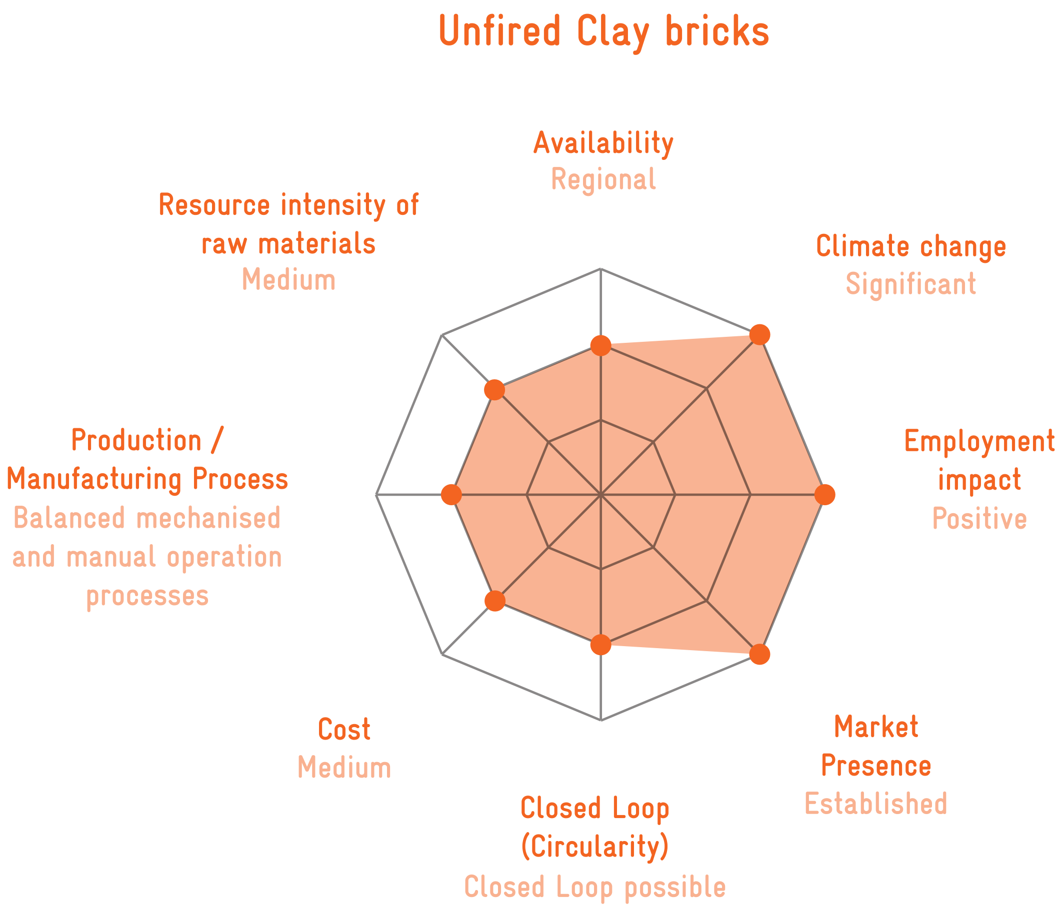
The stones are produced on the spot. Using the site's existing soil, the process minimises production and transport costs, which also greatly reduces the burden on the environment. Processed in vaults, they provide an optimal cooling climate. The compressed bricks can withstand such great compressive forces that they can be used to build load-bearing walls, even with several floors.

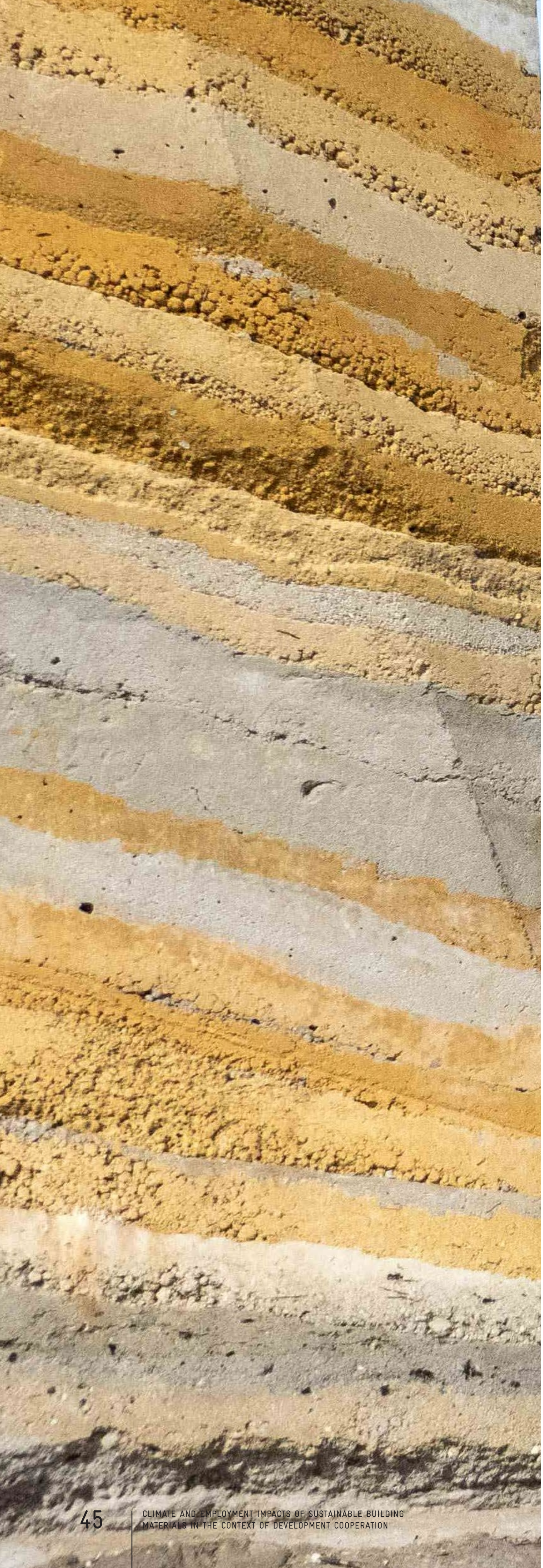
Images © LEVS Architects

Unfired Bricks Summary

Illite used for clay bricks mostly, is one of the most abundant clay minerals in sediments and rocks, and the major constituent of many brickmaking clays all over the world. Depending on regional clay soil abundance.







Rammed Earth

Material Overview

Rammed earth has been used in construction for thousands of years, with evidence of its use dating as far back as the Neolithic Period. Rammed earth walls are formed by compacting damp soil between temporary forms. Together with other forms of unbaked earthen construction, such as mudbrick, rammed earth has a long and continued history throughout many regions of the world. Major centres of rammed earth construction include North Africa, Australasia, regions of North and South America, China and Europe, including France, Germany and Spain. Commonly used in China, the technique was applied to both ancient monuments and vernacular architecture, with the technique used for construction of the Great Wall. Though interest in rammed earth declined in the 20th century, some continue to advocate its use today, citing its sustainability in comparison to more modern construction methods. Over the past fifty years, a number of standards and national reference documents have been published in Australia, Germany, New Zealand, Spain, USA and Zimbabwe. Many of these countries have led the modern revival of rammed earth construction (Maniatidis&Walker, 2003).

Site characteristics, including local climate, topography, wind direction, and sunlight orientation, influence the design of successful rammed earth buildings. Typically, the rammed earth technique works best in climates with high humidity and relatively moderate temperatures. In colder climates, rammed earth walls may need additional insulators, while in locations with high rainfall, they need additional protection against rain.

As rammed earth structures use local materials, they are low embodied carbon, highly and low-waste alternatives to load bearing walls involving concrete and steel. Rammed earth allows the construction of solid load-bearing walls with strong sound insulation. There is a broad variety of soils suitable for rammed earth houses and include sands with sufficient clay and silt, clayey silts, clayey gravel and gravel-sand-clay mixtures. To increase the load-bearing capacity of rammed earth walls, cement is often added into the original soil mixture as a stabiliser. This is referred to as Stabilised Rammed Earth (SRE) in contrast to Rammed Earth (RE) and is common particularly in Australia.

GHG and Environmental impacts

The most basic traditional rammed earth has very low GHG emissions, but the more engineered and processed variant of rammed earth potentially has increased emissions as transportation and the production of cement can add significantly to the overall emissions of contemporary rammed earth construction. As compressive strength of cementitious rammed earth walls is lower to their concrete equivalents, more efficient walls might be achieved through concrete with less material use, which would be beneficial to reduce amount of cement and resources.

With around 9.3 kg CO_2eq/m^3, rammed earth has around 70% reduction potential in embodied energy compared to fired bricks. However, these values depend on raw material extraction, additives, manual manufacturing (casting), and delivery of material to the building site. Especially additives can have a significant influence on the CO_2 impact. Without the use of cement or lime additives, non-stabilised rammed earth has considerably lower embodied carbon than concrete. The main source of emissions in the production of non-stabilized rammed earth structures is the compaction operation (Akbarnezhad and Xiao, 2017). However, since non-stabilized rammed earth is not generally suitable for structural applications, the addition of stabilising additives such as cement is often required. For rammed earth walls with a proportion of 5-10% of lime or cement, the CO_2 emissions will be significantly higher as it is estimated that per 1 kg of cement produced, 0.5 - 0.9 kg of CO_2 emissions are evolved. With increasing binder content, the embodied carbon of rammed earth increases proportionally. Reddy and Kumar show that the embodied energy of a non-stabilised rammed wall may increase from 0.33 – 0.36 MJ/m^3 to 0.4 – 0.5 GJ/m^3 range when about 6% – 8% cement is added to stabilize the wall (Reddy and Kumar, 2010).

Suitable use for construction

Design and detailing of rammed earth buildings implemented in monolithic walls have evolved and developed in recognition of the material's low tensile strength, relatively high drying shrinkage, poor water resistance and low thermal resistance. Thick walls required to provide sufficient mechanical resistance also offer high thermal mass and improved insulation. Rammed earth, as most types of earthen construction, is relatively stronger in compression than it is in bending and shear. Therefore, unreinforced rammed earth should generally only be used for structural elements subject to primarily compressive loads, mainly vertical walls and to a lesser extent, columns. The compressive strength of rammed earth is dictated by factors such as soil type, particle size distribution, amount of compaction, moisture content of the mix and type/amount of stabiliser used. Well-produced cement-stabilised rammed earth walls can be between 5 - 20 MPa.

As a porous material, earth helps to regulate the relative humidity of a space by storing water molecules when the air is humid and releasing them when the air is drier, which allows for perfect health. The density of the soil being high, it contributes to the thermal inertia of the house, by playing a buffer role (storage and destocking of heat). This thermal phase shift is interesting in the Sub-Saharan region, where the temperature difference between day and night is relatively large. Raw soil therefore diffuses the heat of the day during the night and vice versa. It can also contribute to the acoustic and aesthetic comfort of the home. Finally, the soil is fire-resistant.

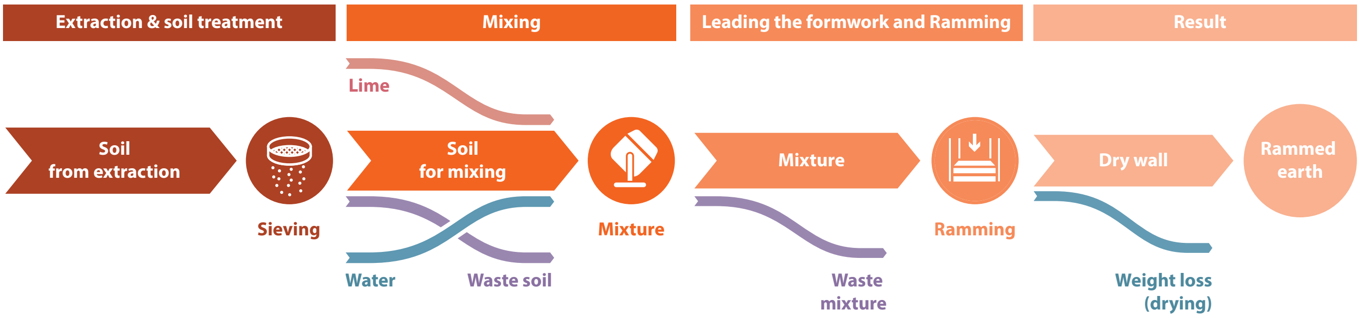


Figure 9 Value chain of rammed earth

Rammed earth buildings in the Hacienda Santa Maria, Tarma, Junin, Pérou. Author: JYB Devot. https://commons.wikimedia.org/wiki/File:PiseP1010653mod.jpg

Production, process and employment effects

The renewed attention paid to raw earth construction in recent decades is linked to its undoubted cost-effectiveness, and low embodied energy. Rammed earth has a short value chain as soil can be obtained locally and, in some cases, directly at site. Soil is sieved, mixed and rammed or precast into compressed earth blocks.

Since the processing does not require a lot of technical skills, it can be practiced by unskilled workforce, creating employment, especially for low-income sectors. It should be noted that raw earth construction and design however requires good knowledge and understanding of soil types in order to obtain the appropriate soil mixture. Building with raw earth, however, does not require specialised manpower, which allows anyone to build a house with resource to simple tools.

However, to date raw earth buildings are limited by the lack of a technical reference standard and by its perception as a low-class material where it is often strived for other materials that reflect status. Besides enabling local population to use the widely available soil material, it is also important to emphasize on its highly competitive price compared to concrete and the thermal comfort provided through the material.

Circularity

Buildings made from rammed earth bind materials for a life span with more than 30 years and are therefore designed for longevity. However, rammed earth as a natural material can be deconstructed and can re-enter the natural cycle. Raw soil is a renewable and even recyclable raw material when it is not processed. Similar to unfired clay bricks, the circularity of rammed earth is depending on stabilizing agents and additives like cement and lime. Without additives, buildings constructed from rammed earth can be deconstructed using manual tools like axes and the material can degrade back into nature as soil (Dabaieh et al., 2020). In cases where cement or lime is added to stabilise earthen buildings it is not possible to recycle the building material. Further, formwork from construction is removable and can be reused, reducing the need for lumber.

Case Study:
Anandaloy, Bangladesh

Location: Rudrapur, Dinajpur district, Bangladesh

Architects: Anna Heringer

Urban Typology: Multi-use community centre

Year of construction: 2018-2019

Materials: Fired brick foundation, mud walls (cob technique), bamboo pillars/ceilings and roof structure, straw roof (lower roof), metal sheet roof (upper roof)

Costs: not disclosed

Constructed from only local materials and with the know-how of local craftsmanship, the Anandaloy project respects local culture and tradition, and with a very simple design manages to integrate a diverse range of both human needs and programmatic abilities without damaging the environment.

The construction of the building with a footprint of 250 m^2 includes a fired brick foundation, mud walls (cob technique), bamboo pillars/ceilings and roof structure, straw roof (lower roof), metal sheet roof (upper roof).

The building hosts a therapy centre for people with disabilities on the ground floor and a textile studio on the top floor producing fair fashion and art. Architecturally, the building explores the plastic abilities of bamboo and rammed earth in order to create a stronger identity and thereby to celebrate nonconformity and diversity. Rather than being straight-lined, the building dances in curves, a ramp winding playfully around its inner structure.

In the beginning the building was planned as a therapy centre only, but the designers were able to extend the building with another storey, hosting Dipdii Textiles, a studio for the female tailors in the village. This part of the building's programme is co-initiated and taken care by Studio Anna Heringer in order to allow women to find work in their villages. It is a counteract to urban-rural migration. The concept was not only to provide therapeutic treatment but also provide an opportunity to learn and work in that building and engage in the community there.

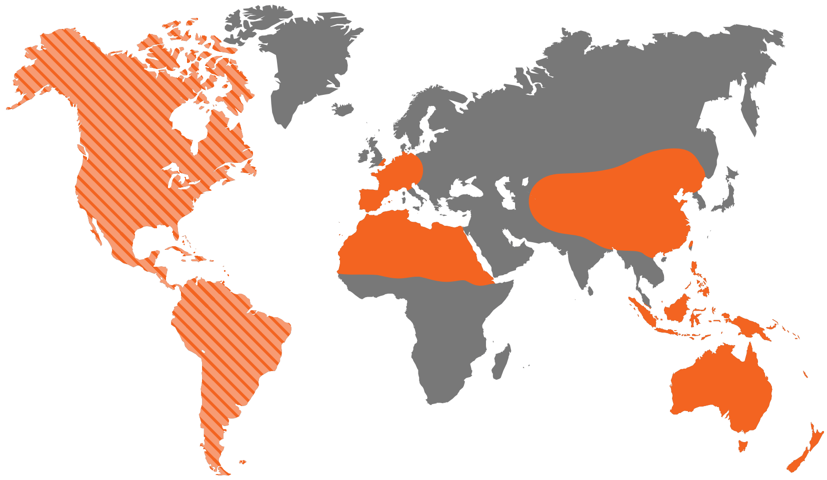
Because the Anandaloy project is mainly built out of mud and bamboo from local farmers, the biggest part of the budget was invested in local craftswomen and -men. Thus, beyond the building's structure, it became a real catalyst for local development.

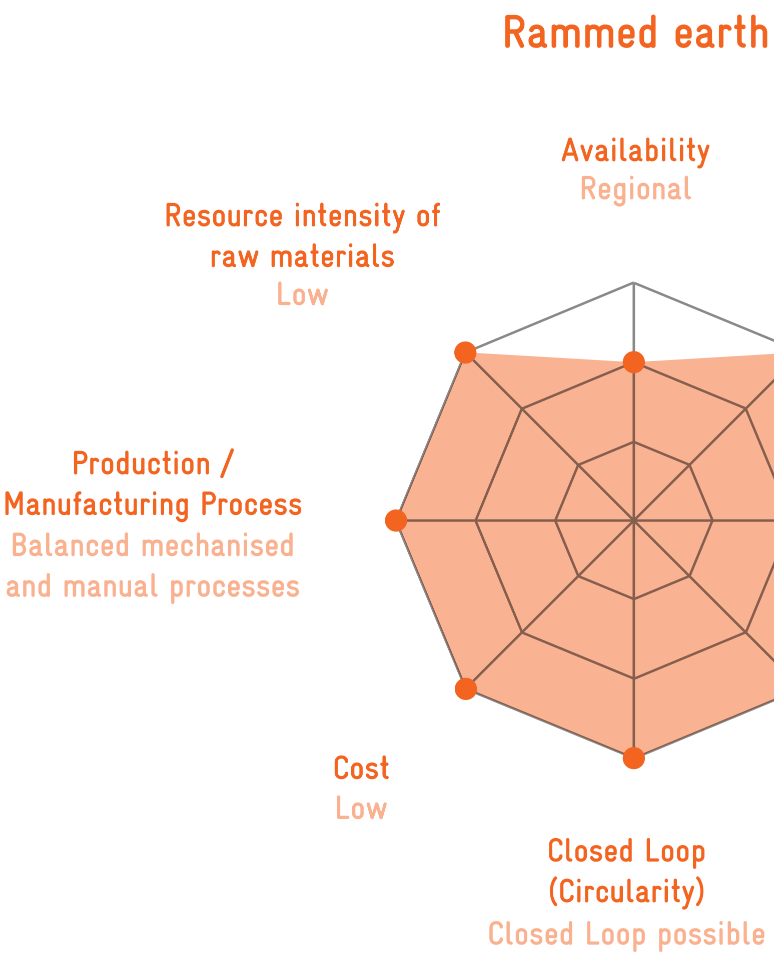
To show the beauty and capacity of mud, it is important to bring out the best of it and not just to treat it as a cheaper version to brick. With that particular mud technique, called cob, no formwork is needed, and curves are just as easy to be done as straight walls.

Images © Kurt Hoerbst 2018/2019

Rammed Earth Summary

Together with other forms of unbaked earthen construction, such as mudbrick, rammed earth has a long and continued history throughout many regions of the world. Major centres of rammed earth construction include North Africa, Australasia, regions of North and South America, China and Europe, including France, Germany and Spain.





3.4 Supplemental Cementitious Materials

The use of supplemental cementitious materials (SCMs) represents an important means of offsetting the use of cement for concrete. SCMs are fine particulates which are either pozzolanic or cementitious in nature that react when hydrated to form cementitious compounds. SCMs are used to replace a portion of the ordinary Portland Cement (OPC) in concrete and cement-stabilized masonry materials while maintaining or enhancing performance characteristics (like compressive strength and durability) (Easton, 2014). Natural and artificial mineral admixtures such as fly ash, bottom ash, ground granulated blast furnace slag (GGBS) possessing high pozzolanic properties have been already established as a cement replacement in many regions. Such admixtures, originating from various industrial and agricultural by-products, can significantly enhance the physical and chemical characteristics of cement and concrete.

Industrial-based SCMs

Material Overview

The most commonly used admixtures, fly ash (FA) and GGBS are well established in countries affiliated with steel industries. GGBS manufactured from a by-product of the iron-making industry is obtained by quenching molten iron slag resulting from iron and steel-making from a blast furnace in water or steam to produce a granular product that is then dried and ground into a fine powder. The cementitious properties of blast-furnace slag were discovered in the late 19th century and it has been widely used in concrete manufacture for over 100 years. GGBS is high in calcium silicate hydrates (CSH) which improves the strength, durability and appearance of the concrete. FA is a by-product of coal combustion in power plants that is composed of the particulates (fine particles of burned fuel) that are driven out of coal-fired boilers together with the flue gases. FA is often used as a pozzolan to partially replace Portland cement in concrete production. Pozzolans ensure the setting of concrete and plaster and provide concrete with more protection from wet conditions and chemical attack.

However, both FA and GGBS have limited and only regional availability and are by-products of carbon intense industries which are connected to a variety of adverse environmental impacts. Further, a stronger demand for industrial by-products could lead to shortages once industries for steel are moving towards low energy processes. Therefore, SCMs resulting from industrial processes should only be used while agro-based SCMs or further alternatives are further tested and developed.

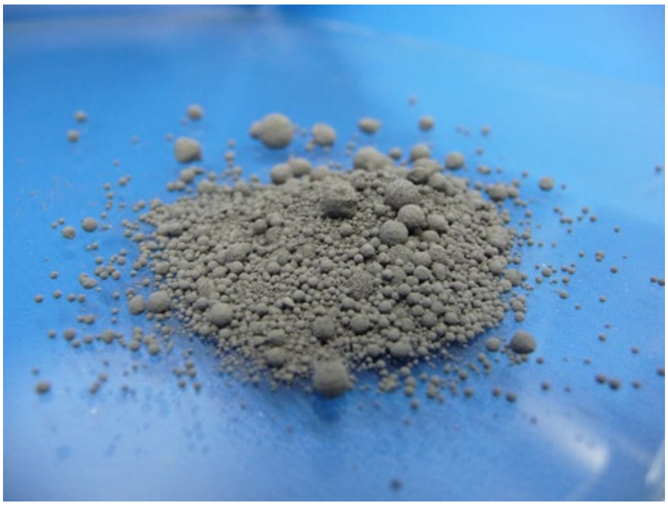
GHG and environmental impacts

There are environmental benefits to be gained from the use of industrial by-products as a cement substitute, both in the production process and throughout the life of the structure. Because they are waste products of industries and the slag or ashes would be created regardless of whether or not it can be used, FA and GGBS are thought to generate very low CO_2 emissions. Producing 100 m^3 of concrete uses 32 tons of cement. Replacing 50% of that cement with GGBS saves around 13 tons of CO_2 (Building, 2015).

Other sustainability benefits of GGBS and FA include the fact that they produce very low sulphur dioxide and nitrogen dioxide, both harmful gases, and that it requires virtually no quarrying or mineral extraction as it can get delivered directly from steel production plants or coal plants.

Suitable use for construction

GGBS is widely used in Europe, and increasingly in the United States and Asia (particularly in Japan and Singapore) and as one of the most common substitutes several standards exist globally for the use and specification of GGBS in concrete production (Malagavelli and Rao, 2010). Concrete with industrial by-products as cement replacement can be used the same way as conventional concrete with similar structural properties (Building, 2015). GGBS contains the same oxides and undergoes the same hydration process as cement. Additionally, GGBS reacts with the excess calcium hydroxide to form calcium silicate and calcium aluminate hydrates which contribute to filling and blocking the pores within the crystalline structure. The result is a hardened cement paste with a refined pore structure that is less permeable. GGBS typically replaces around 50% of the Portland cement, but up to 95% can be used in specific applications.



Images: Popiół lotny do betonów (Fly ash) Autor: Ablazejo
https://commons.wikimedia.org/wiki/File:Popi%C3%B3%C5%82_lotny.JPG

Images: Ein Haufen Flugasche Autor: Mailtosap
https://commons.wikimedia.org/wiki/File:Flugasche.jpg

Images: Fly ash bricks (Tamil Nadu, India) Autor: Thamizhpparithi Maari
https://commons.wikimedia.org/wiki/File:%22Fly_ash_bricks%22.jpg

Production, process and employment effects

GGBS emerges as a byproduct during the melting process of iron. Blast furnaces operate at temperatures of up to 2,000 °C and are fed with a mixture of iron ore, coke and limestone. The iron ore converts to iron, which sinks to the bottom of the furnace. The remaining materials form a slag that floats on top of the iron. The molten iron and slag are drawn off at regular intervals from the furnace. After being tapped from the furnace and separated from the iron, the slag is rapidly quenched in water. This process is known as granulation because it produces glassy granules, similar in appearance to coarse sand with excellent cementitious properties. The granulated slag is further processed by drying and then ground to a very fine powder in a mill (Building, 2015).

Blast-furnace slag has been widely used in concrete manufacture for over 100 years and build a well-established role on the market. Coal FA and GGBS are currently mostly used in the cement industry as they form an already well-established cement admixture. Producers are typically large power plants or industries. However, a stronger demand for industrial by-products and also more renewable steel and energy production processes could result in shortages of FA and GGBS from medium- to long-term, which could lead to agro-based SCM becoming more popular as alternative admixtures.

Circularity

At present there are no studies on the behaviour of recycled concrete using SCMs It can be assumed that SCM concrete would behave similarly to normal concrete which means it could either be crushed and used as aggregates or reused with new SCMs and cement.

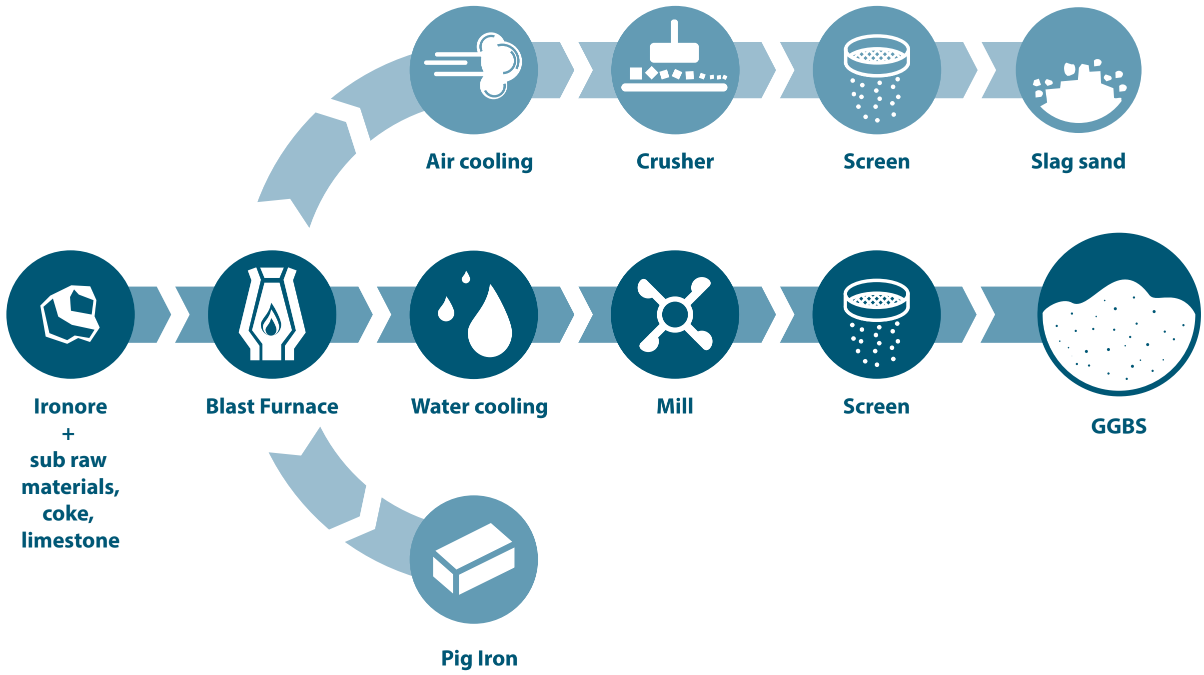


Figure 10 Production process of GGBS through iron processing

Case Study:
102 Rivonia Road

Location: Johannesburg, South Africa

Architects: Boogertman + Partners

Urban Typology: Multi space with offices, retail, hotel, residential

Year of construction: 2015

Materials: FA concrete

Costs: not disclosed

102 Rivonia Road consists of two main buildings with connected walkways in-between to create a sense of connectedness and encourage collaboration between different areas of the office. The 40,000 m² office space is home to EY Africa's headquarters in one tower and various other tenants in the second tower. Its form is comprised of three elements: a seven-storey building with an active atrium space animated by transecting stairs and bridge links, together with a thirteen-storey office tower, connected by a five-storey-high link bridge that allows for future flexibility. Both towers stand on a nine-level underground parking garage.

It was designed with sustainability in mind, being 50% more sustainable than the average office building with a 4-star Green Star South Africa rating. Air cooled chillers and fire system that recycles used water also contributed to the project's energy efficiency. The high amount of FA used allowed a 30% decrease in Portland cement use, lowering the embodied carbon footprint of the project. 80 MPa concrete was produced that way, achieving at ambient temperature with no steam curing or anything like that to increase the carbon footprint. The building was designed to be 50% more energy efficient by reducing operational carbon emissions by more than 130 $kgCO_2/m^2/year$.

Images © Boogertman + Partners 2015

Agro-based SCMs

Material Overview

Agricultural by-products like rice husk ash (RHA) are renewable resources with low levels of toxic components and may be used as pozzolanic material in blended cement or incorporated directly in concrete mixtures (Kishore et al., 2011; Gursel et al., 2016). Rice husk, an agricultural waste product arising from rice mills in the milling process of paddy is abundantly available at virtually zero costs in several countries of the Global South and offers an eco-friendly and durable alternative option for cement replacement (Ramchandra et al., 2015; Ramchandra, 2016). However, as rice husk is a waste material, it is largely abundant in many countries with rice production although it is not yet extensively utilised in the construction industry. This is probably due to a lack of knowledge of the material's characteristics when blended with cement or used in concrete (Msinjili & Schmidt, 2014). While industrial by-products are independent of seasonality, rice husk and other agro-based cement alternatives experience seasonal impacts of the availability of material as manufacturing is completely dependent on the production of rice paddy.

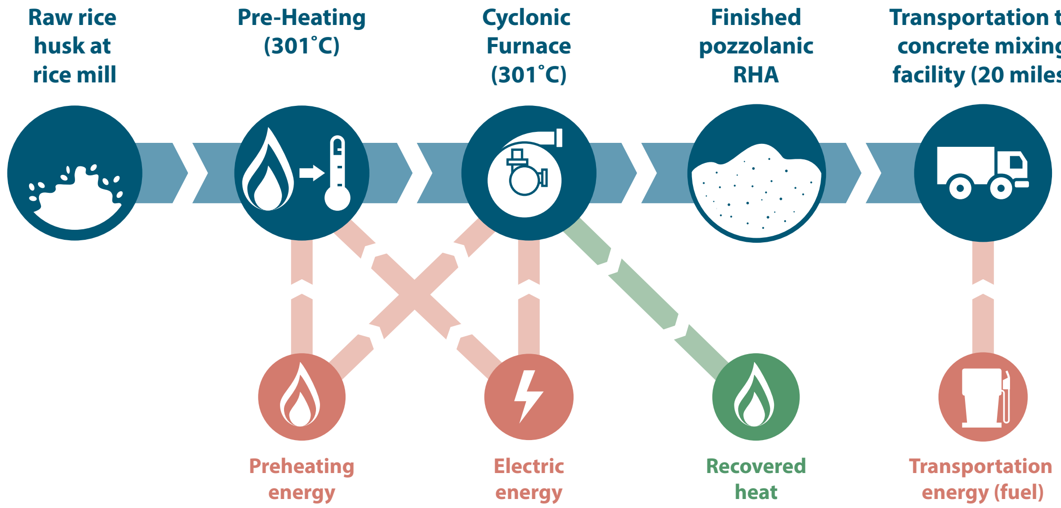


Figure 11 Rice husk ash life cycle overview. Green represents energy produced, and red energy consumed.

GHG and Environmental impacts

Rice husk is a very abundant yet unused and mostly burned or landfilled material. Around 480 million metric tons of rice husk are produced annually in Asia and the United States and more than 300 million metric tons in Brazil based on current unmilled rice production. Although RHA is not typically added to cement in concrete production, the production of more cement using RHA could have far-reaching environmental implications. Knowledge of the embodied energy difference between RHA and OPC would be an impetus to increased use of RHA in building materials (Henry and Lynam, 2020). Studies showed that replacing 20% of OPC by RHA in concrete can result in a CO_2e reduction of 24% in the concrete production chain. However, this value can only be obtained if RHA is produced in a fluidised bed at low temperatures and is also dependent on the transport of RHA to construction site.

In a study of Henry and Lynam (2020), the embodied energy of rice husk ash was assessed and compared with embodied energy resulting from the production of conventional concrete. In the study, it was assumed that energy recovered from burning the husk material is used for drying at the rice mill and combustion of rice husks as well as transportation of RHA were considered in the study. Henry and Lynam found that the production of RHA is highly energy efficient, with a value of embodied energy of -26 MJ per kg of RHA, with the negative sign indicating that energy is produced in the overall process. Comparing the embodied energy of RHA with that of OPC ranging between +4.6 MJ/kg (Hammond and Jones, 2008) and +6.4 MJ/kg (IFC, 2017) shows the potential for more sustainable building materials when incorporating RHA with OPC. With the large amounts of rice husk arising every year through rice production, a further environmental benefit would be the deviation from landfill or open burning of rice husk.

Suitable use for construction

Depending on the composition and proportional usage of RHA in concrete, the incorporation of RHA as an SCM in conventional concrete can enhance the compressive strength. While the use of RHA up to 15% shows the highest improvement, the compressive strength reduces beyond the 30% RHA replacement level. This shows that an appropriate proportion of RHA is necessary, as higher doses tend to adversely affect the concrete strength. In terms of strength development, it has been shown that the RHA concrete achieves about a 60% hydration within 7 days but has increased strength development at later curing days (28, 91 and 180 days). This is primarily because of the high reactivity of the RHA particles at longer curing days. However, use of chemical activators can cause a sharp rise in the 7 days compressive strength (Amran et al. 2021). The addition of RHA in cement and concrete not only increases the compressive strength but also improves corrosion resistance, insulating behaviour and durability (Krishna, 2012).

Although significant research on RHA as cement replacement has been undertaken, the material continues to be a pioneering material in exploration phase. So far, no practical examples are known of RHA being used as cement replacement for constructed projects.

Production, process and employment effects

Rice husk is produced in rice mills in the milling process of paddy. Following the burning process of rice husk, RHA is obtained. The husk is used as fuel in the parboiling process to produce steam. In the firing process of rice husk, husk has approximately 75% organic volatile substance and remaining 25% weight of husk is transformed into RHA. RHA contains about 80-90% amorphous silica. In every 1000 kg of paddy, approximate 22% (220 kg) of husk is produced, and around 78% (780 kg) of rice is produce. In the milling process when the husk is burnt in the boiler approximate 25% (55 kg) of RHA is produced. RHA at proper incineration conditions with temperatures not exceeding 650°C with constant air access is found to contain 85 – 95% amorphous silica with high pozzolanic properties suitable for cement replacement. While the incineration takes about 30 minutes, the natural cooling of the burnt ash takes 24 hours in a dry area immediately after burning (Gautam, Batra, Singh, 2019).

Production of agro-based SCMs could have positive impacts on local value chains, as they are waste products which are not commercially used yet. Since rice or other agricultural by-products can be used to produce SCMs, the product is not locally or regionally restricted. Further, rice husk is produced as a by-product already and therefore does not have to compete with other agricultural uses. However, manufacturing is completely dependent on the production of rice paddy. The production of supplementary cementitious materials does not require complex and technical machinery and could therefore strengthen local SMEs or even local farmer to generate more income. However, more complex technical knowledge is necessary when mixing and allying concrete using SCMs in construction projects.

RHA can substitute from 5% to 30% of cement in a concrete mixture, depending on the application. The cement industry is large enough to support the use of a significant amount of the RHA produced. Especially in developing countries cement production is still growing at high rates which makes this market sustainable for the long term. At present, only a few studies have conducted cost analyses on the application of agro-waste, mainly RHA in cement. A complete economic analysis with most agro-wastes is not reported, which is necessary for their future application in construction. However, industrial additives to concrete such as FA or GGBS still build a barrier towards market uptake of agro-based SCMs since their implementation in construction projects is already established and cost-effective. Coal FA is currently mostly used in the cement industry as it is an accepted cement admixture. Coal FA producers are typically large power plants or industries with more resources to push the use of coal FA than agro-based SCMs.

Circularity

At present there are no studies on the behaviour of recycled concrete using SCM. It can be assumed that SCM concrete would behave similarly to normal concrete which means it could either be crushed and used as aggregates or reused with new SCM and cement.

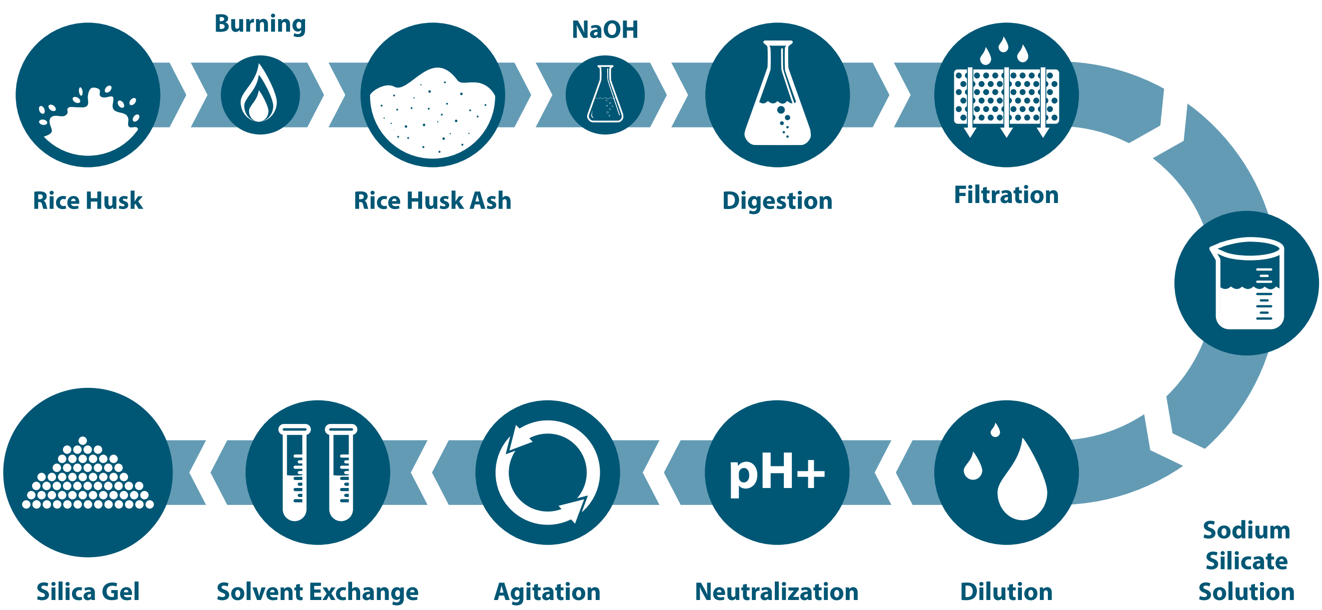
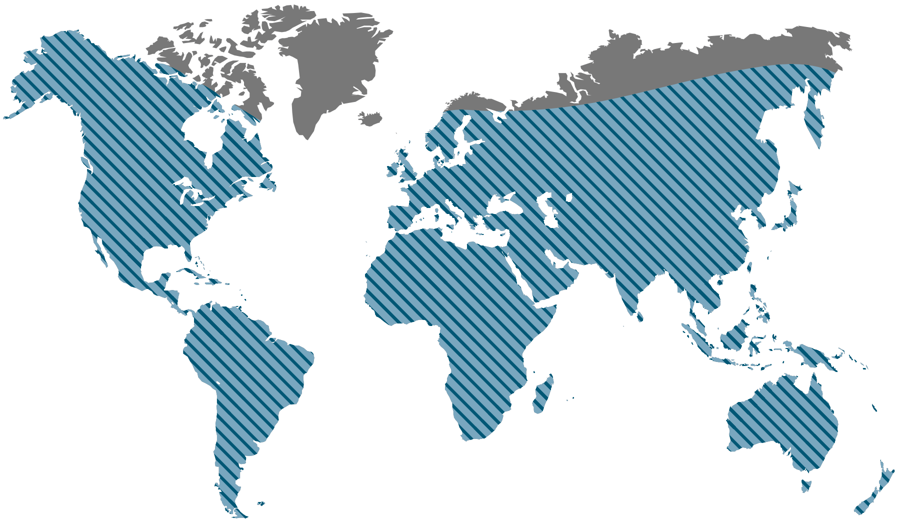
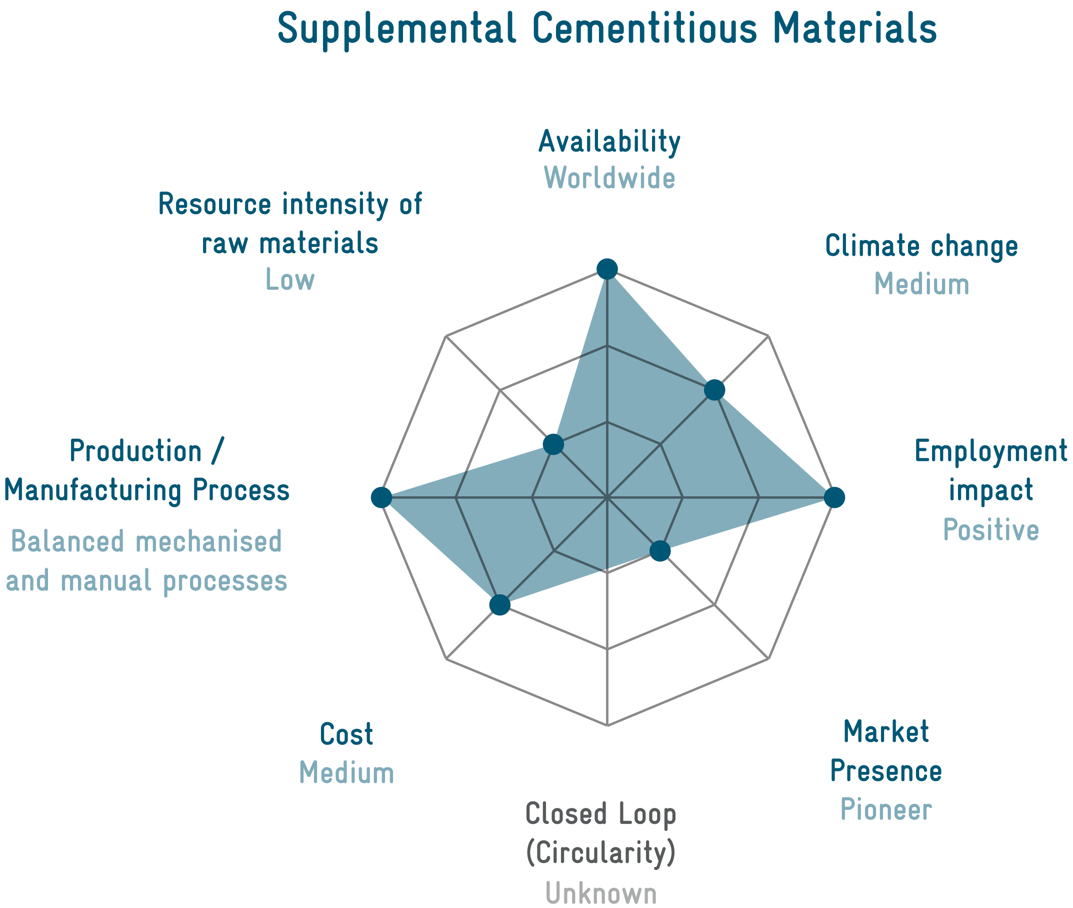


Figure 12 Production process of RHA

Supplemental Cementitious Materials Summary

Possibly worldwide but depending on regionally used agro/bio elements.





3.5 Alternative concretes

This chapter focusses on the field of alternative concretes with potentials of local production such as concretes from desert sand and cement alternatives containing industrial or agro-based supplementary cementitious materials.

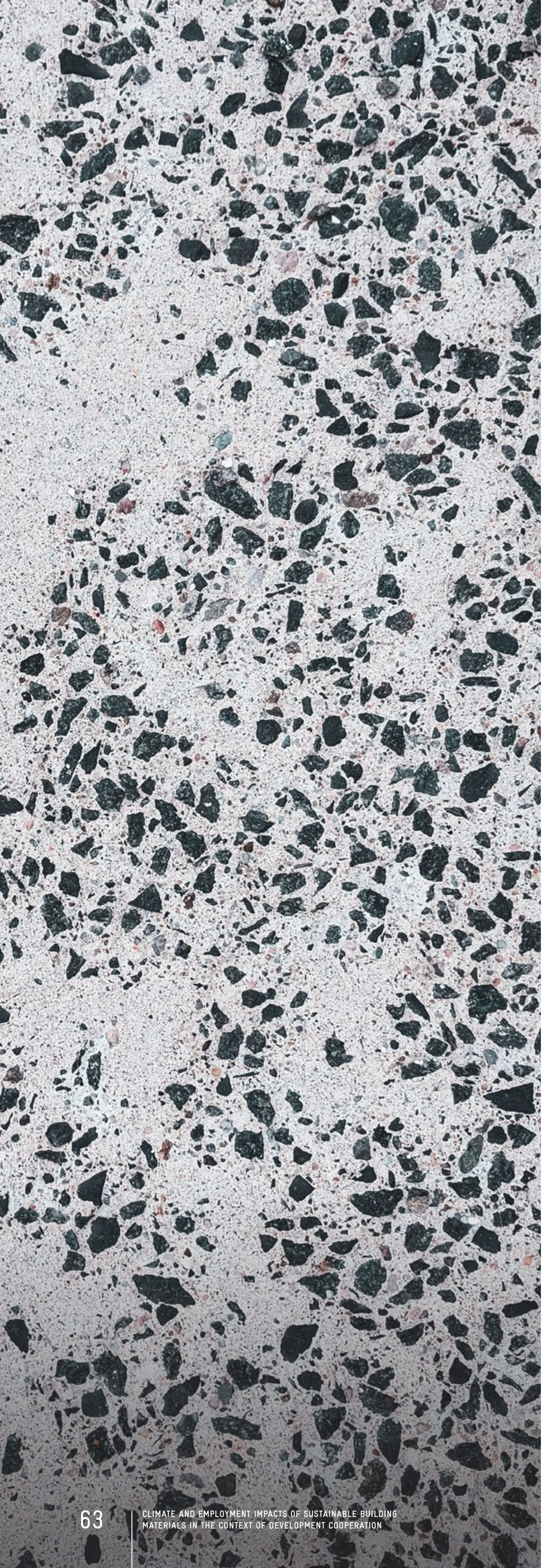


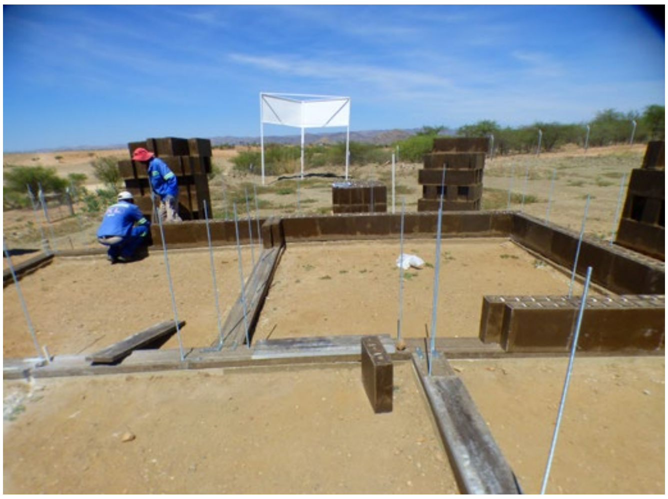
Photo by Sigmund on Unsplash

Polymer Concrete

Material Overview

Polymer concrete composites (PCC) made from industrial or agricultural waste are becoming more popular as the demand for high-strength concrete for various applications is increasing. Polymer concrete composites not only provide high strength properties but also specific characteristics, such as high durability, decreased drying shrinkage, reduced permeability, and chemical or heat resistance. PCC, which incorporate waste products and technologically advanced substitute materials such as SCMs and aggregates, are an effective, inexpensive, and eco-friendly way to improve quality of concrete buildings. PCC usually have a lower carbon footprint than traditional concrete as no cement is used in the process which is the main CO_2 source in the production of traditional concrete. The idea of polymer concrete started in the late 1950s where these materials were designed to be used as a substitute for cement in specific construction applications (Alhazmi et al., 2021). Polymer concrete was first used for construction cladding and other applications. It was widely adopted as a repair material afterwards due to its fast cure time, superior bonding properties, ability to reinforce steel, improved strength, and toughness (Fowler, 1999).

PCC can be produced and used in large-scale construction projects all over the world. The aggregates are bound together by the polymer matrix monomer, and the produced composite is known as concrete. Agricultural, municipal, and industrial wastes such as RHA, FA, furnace slag, silica fume or waste glass are used as supplementary cementitious materials in making polymer concrete. The production process varies as it depends entirely on the composite materials to be used as well as target strength. One possible polymer concrete that will be presented here is a combination of naturally occurring sands and a resin as polymer binder. The sands are widely available raw materials such as desert sand, overburden material from the mining industry or even standardised sand, which usually would not be used for conventional concrete production. The binder based on an unsaturated polyester resin mixture which is produced to a large extent from recycled Poly-Ethylene terephthalate, more known as PET (Polycare, 2021). This technology allows to produce polymer blocks made of durable and environmentally friendly polymer concrete. So-called Polyblocks are made by polymer concrete which consists 90% filler of naturally occurring sands and 10% binder.



Namibia - Two Bedroom House, Image © Polycare 2019

GHG and Environmental Impacts

Regarding raw materials, GHG emission arise mostly through the resin/binder production as well as through the transport of raw materials and construction blocks. For the example of Polyblocks, the binder is partially made from recycled PET bottles which need to be sourced, collected, transported and processed to act as a binder in the block production. The production process requires energy for the machines to mix the filler with the binder and to press the blocks. As Polyblocks are containing sand, their weight lies between 5 kg for a simple and 70 kg for a window frame block and climate impacts depend largely on transport distances (Polycare, 2021).

Suitable use for construction

As the material is still in a pioneer phase, polymer concrete is often used in specialized construction projects where there is a need to resistant several types of corrosion and is supported to have durability i.e., to last-long. The life span of polymer concrete is expected to be up to 100 years. However, a lack of experimental evidence of the fire resistance exists, and the behaviour at high temperatures must be studied based on a detailed analysis of their mechanical characteristics.

With a compressive strength of 120 Nm/cm^2, it can be used similarly to ordinary concrete. Studies have shown that after one day of soaking at room temperature, polymer concrete reaches about 70% to 75% of its strength. Normal concrete normally produces a 20% strength gain after one day of curing. So far, construction up to two storeys has been achieved but since strength and durability are comparable or exceed traditional concrete, different building types are possible. From a structural point of view, 3 storeys would be possible with the blocks alone, but higher buildings would possibly need reinforcement. However, as the technology is still in a pilot phase, polymer concrete is often considered to be more expensive than conventional concrete.

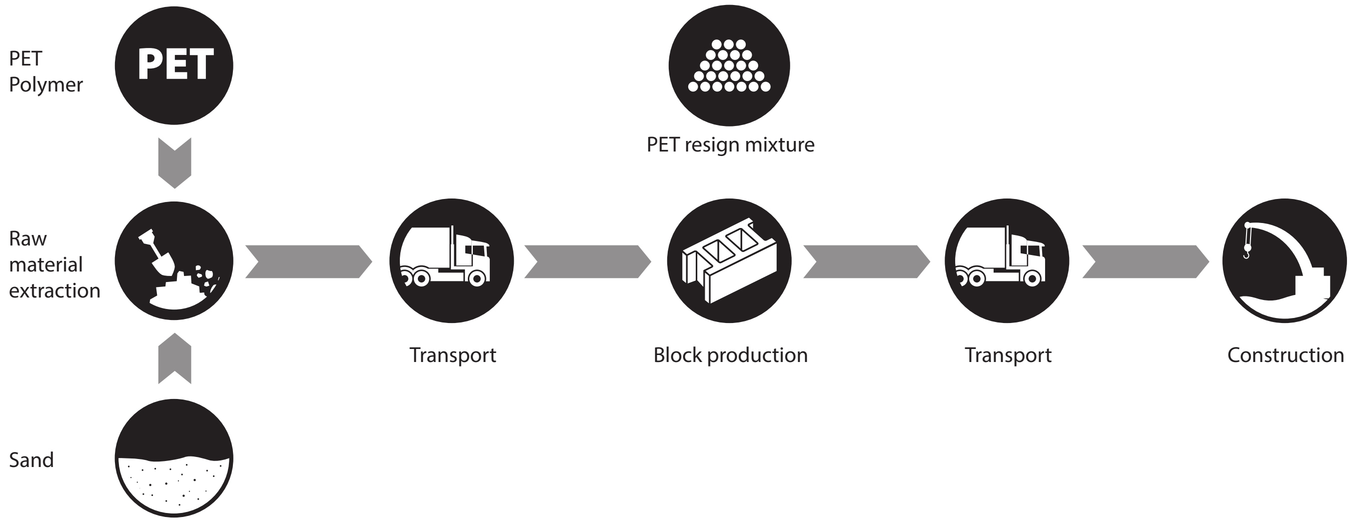


Figure 13 Value chain and manufacturing of polymer concrete

Production, process and employment effects

For polymer concrete, various raw materials can be used ranging from desert sand, silica sand or foundry sand can help making use of local resources to shorten transport of raw materials. In order to minimize the drying shrinkage in the aggregate blend and thus improve the properties of polymer concrete, a micro filler is often applied to a mix (Alhazmi et al., 2021). Micro fillers from agricultural, municipal, or industrial wastes materials are then combined with a binder consisting of (recycled) PET. Polymer concrete does not need any water for the production, which is an advantage for semi-desert climates.

A factory for polymer concrete designed for local conditions can be set up in 4-6 weeks and is easily scalable (Polycare, 2021). The local extraction of raw materials (desert sand) as well as setting up factories creates new jobs as well as setting up the factory and factory workers. With regard to the effects on informal markets, necessary raw materials (i.e., PET from recycled plastic bottles) creates demand on recycling market which is often largely run by informal waste pickers. To work in the production process, staff needs to be skilled to know how to use production recipes etc. The production of Polyblocks is not affected by seasonality effects due to the material (desert sand, PET) is available throughout the year (Polycare 2021). For the example of Polycare, the first factory in Namibia employs around 20 people in the direct manufacturing process as well as further 10 people for other processes such as preparation of materials and primary processing. While binders were produced and imported from Europe initially, regional binders are now used to keep most production processes local.

While the certification/standards for construction has already been granted in various African countries, the approval for polymer concrete as a building material in European countries is still in its infancy. This shows how opportunities for innovation in countries of the Global South especially African countries can drive sustainable construction processes in other regions.

Circularity

Buildings made of polymer concrete bricks can be disassembled at the end-of-life stage of a building and the bricks are ready to be reused as whole for other buildings. Polymer concrete has a life expectancy of up to 100 years and the high durability of the polymer bricks technically allows for an everlasting reuse. Although the material components such as the binder or Styrofoam for insulation cannot easily be dismantled and recycled, the bricks can be reused many times replacing the use of virgin materials and energy use for manufacturing processes. Reuse is more favourable than the recycling (often downcycling) of materials and as the polymer bricks show, reuse is more likely to happen if it is factored early into the planning and demolition process.

Case Study:

Namibia - Two Bedroom House

Location: Namibia

Architects/Developer: Polycare

Urban Typology: Residential House

Year of construction: 2019

Materials: Polymer concrete blocks, metal

Costs: 22.000$

The one storey house in Namibia provides space for 4 - 5 people on 50 m^2. The wall system is built on the prepared foundation which is made of special Polycare blocks. The electrical and plumbing installation takes place when the walls are being built, whereby cables and pipes can be laid within the stones. Sandwich panels are used as the roof, which do not require a roof substructure. The roof pitch is created by an additional row of poly blocks on the front of the house and windows as a gable or, alternatively, a corresponding wooden structure. Windows and doors have been installed conventionally by screwing and sealing. In addition to the necessary trades (sanitary, electrical, etc.), the wall system, together with the roof and windows / doors, has been set up by 2 unskilled workers and a supervisor within 5 days.

A compact, stable base layer such as tamped clay soil, or conventional strip or flat foundations made of cement concrete is sufficient as a foundation. The wall system consists of poly blocks, of which there are 6 different standard types. The smallest stone is 20x10x30 cm and weighs 5 kg. The largest stone is 60x20x30 cm and weighs 15 kg. The stones consist of an insulation core. Made of EPS or rock wool and a shell made of polymer concrete.

The basis of the wall system is a base strip, which corresponds to the floor plan of the house and into which threaded rods are screwed at defined intervals. Building on this, polyblocks are stacked in rows and with staggered joints. Window and door lintels, also made of polymer concrete, are set and after the last row of stones follow, similar to the base strip, a cover strip and above the ring anchor. The ring anchor is then clamped to the base bar by means of the threaded rods and nuts, which gives the wall its static stability. Mortar or glue are not necessary.

In addition to the use of regional sands or secondary raw materials (foundry sands, building rubble), which are usually not suitable for conventional cement concrete production, and the fast and simple construction method, which can also be implemented by unskilled workers and without special machines or special tools, the CO_2 savings of 60% compared to comparable conventionally built houses (with hollow concrete blocks) play a major role.

Image © Polycare 2019

Polymer Concrete Summary

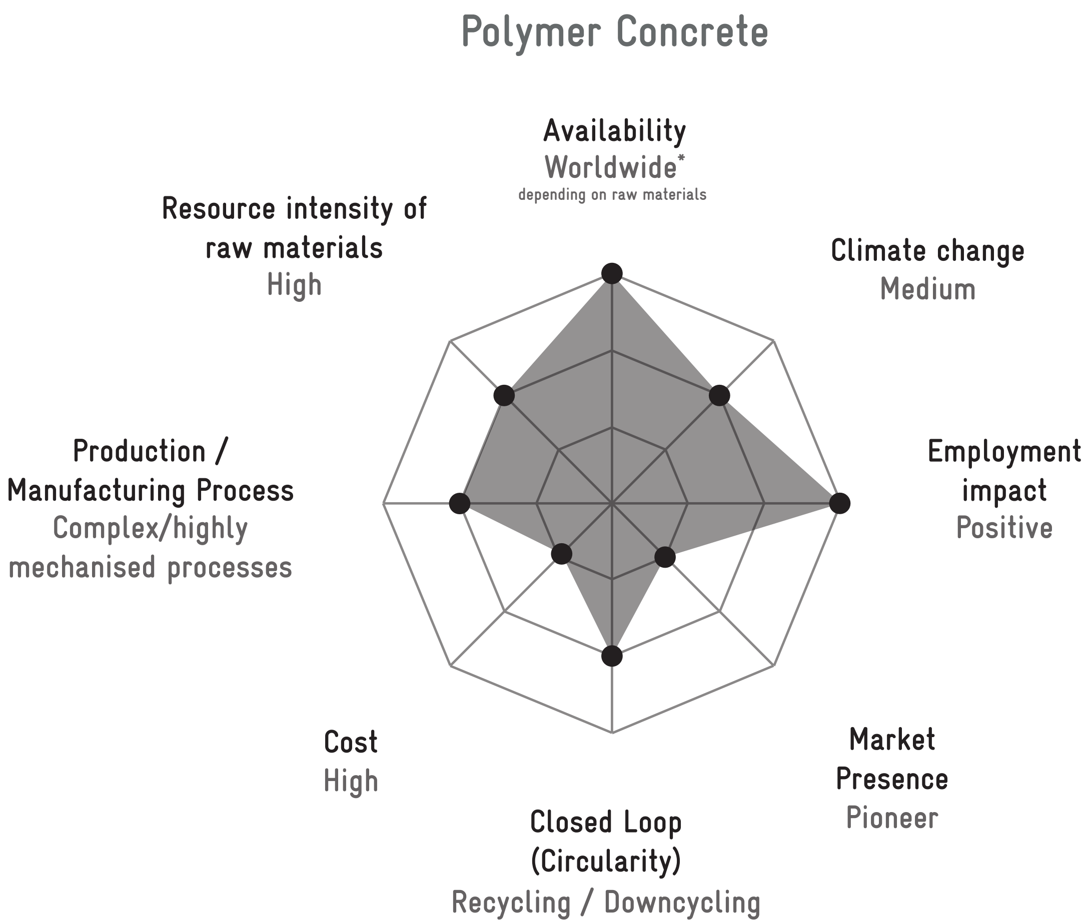
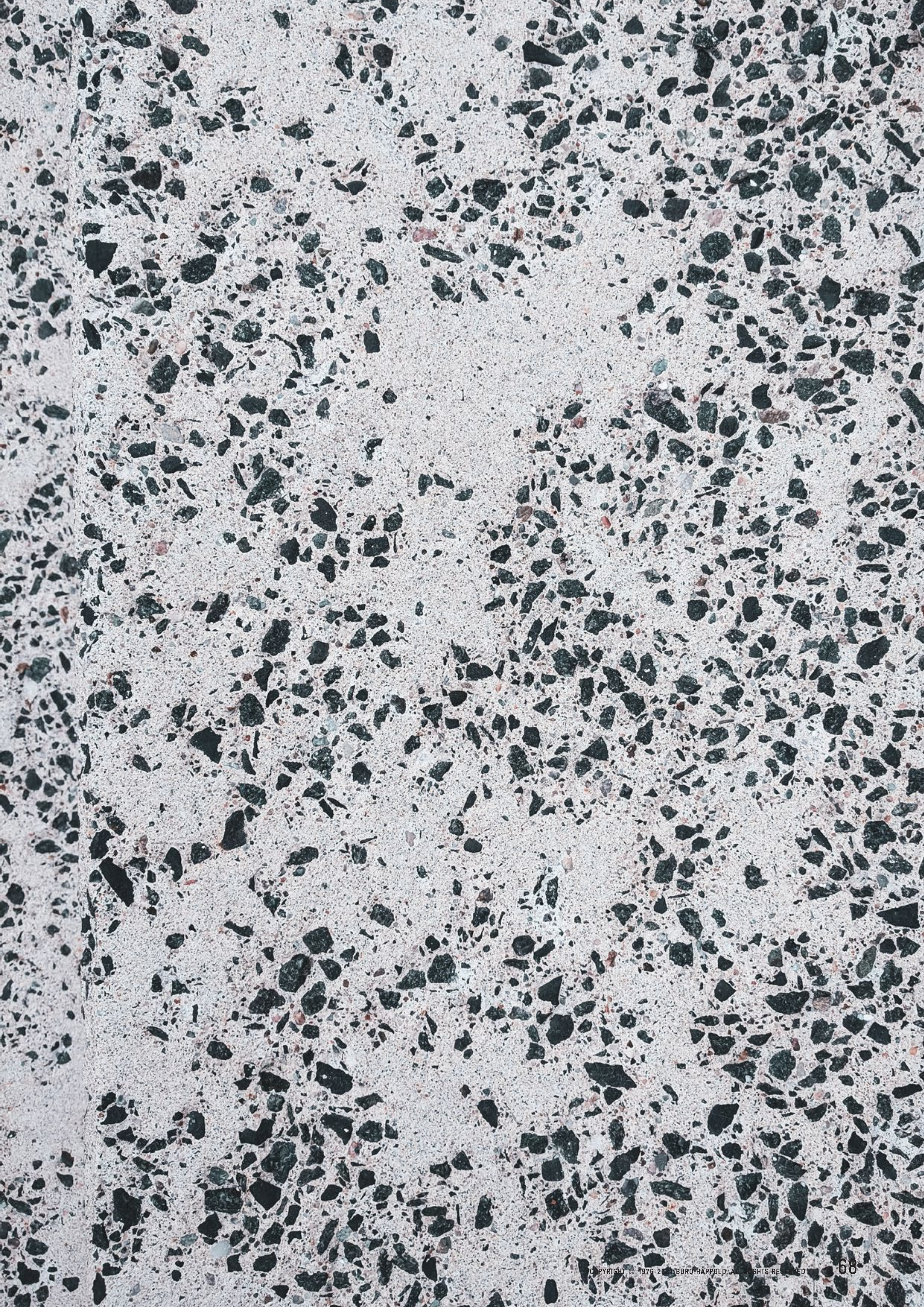


Photo by Sigmund on Unsplash



3.6 Reused & Recycled Materials

Recycled materials, especially from construction and demolition waste will be more abundant and become widely available as construction materials in the future. Recycling materials build a very heterogenous group and it remains challenging to assess all environmental advantages as well as challenges for each individual waste-based product. Therefore, in this section, one recycling (concrete) as well as one reuse material is assessed (reused bricks) and will focus on reused bricks and recycling concrete.

Reused & Recycled Materials

Material Overview

Waste-based materials are gaining momentum due to the environmental impacts of virgin materials as well as shortages of raw materials in the construction industry. Especially construction waste shows a great abundance since the construction industry generates the greatest quantity of solid waste (Xiao-Shuang, et al., 2010, Deng et al., 2008). The main benefits of recycling are (i) saving of natural raw materials, (ii) saving of energy, (iii) decrease of harmful emissions and (iv) adverse impacts on biodiversity. The degree of benefits varies with the kind of material and form of recycling (Thomark, 2000). Recycling materials suitable for building construction include recycled concrete or other non-construction waste-related materials such as recycled paper or plastics. Next to recycling materials, construction materials can also be reused if disassembled correctly. Especially materials such as used timber, clay bricks, steel or aluminium have great potential for reuse. As such materials stem from discarded construction materials and everyday waste, their regional availability is not restricted. However, they are bound to local recycling markets. As formal recycling infrastructures are often underdeveloped in countries of the Global South, many recycling materials still have little or no value, resulting in uncontrolled disposal in a landfill. At the same time, the development of such infrastructures could establish new markets for undervalued waste materials creating local employment opportunities.

Although recycled materials have been gaining more interest over the last years, there are barriers towards implementation related to lack of awareness for the advantages of these materials which often leads to higher prices. In most countries, markets for recycled materials are not yet established and during demolition the different types are often not sorted, cleaned and processed for further usage but will go to landfill directly. In the future, so-called material passports might be a way to assess, quantify and mine possible construction material from buildings at their end-of-life by disclosing data describing material or product characteristics and potential ways for recycling and reuse.

Reused Bricks

GHG and Environmental Impacts

Overall, compared to virgin materials, the GHG footprint of many recycling materials is reduced significantly, as resource and energy use for processing secondary raw material is significantly lower to non-existent, if used goods are repurposed directly. However, reduction GHG reduction potential strongly depends on the resource type - while recycled concrete, gypsum and mineral wool requires GHG-intensive processes and additives when reused, clay bricks and steel allow for far-reaching carbon mitigation.

The results from a study on using recycling materials for the construction of a residential detached house of 150 m^2 in Sweden (Thormark, 2000) show that there are considerable environmental benefits to be derived especially from the use of reused clay bricks instead of new bricks. In case of this project, bricks make up the largest share of building material used in the project, therefore having a huge leverage in contributing to a significant reduction of the environmental impact of the whole building. An important issue, however, is how far the bricks are transported. The length of the feasible transport distance for reused bricks ought to be assessed in each case. The main factors that affect the reasonable distance are distance to the producer of new bricks, the quality of the new bricks and all means of transport. When reused bricks from the local region are used, however, there seems always to be considerable environmental effects. Figure 2 shows the CO_2e contribution resulting from different materials. Replacing clay bricks with reused bricks has a significant impact on GHG emission reduction. Embodied carbon emissions for reused bricks can be as low as 5 kg CO_2eq/m^3 compared to new fired clay bricks with 530 kg CO_2eq/m^3, accounting for an emission reduction potential of nearly 100%.

Suitable use for construction

Bricks especially allow for reuse due to their durability and longevity, while being applicable to all different kinds of building types and regions. Depending on their quality, reused bricks however might lack compression strength and case-to-case examinations are required, before using as structural elements – additional reinforcements could be required. Also, reused bricks often are sensitive to colder climates, exacerbating existing weaknesses, and should not be utilised for exterior load-bearing structures in such regions. Depending on the condition of the bricks, they can be reclaimed, cleaned and reused as a whole for construction. If bricks are in poor conditions, they can also be crushed and turned into bricks powder or aggregates to enter the materials cycle again by being used for new bricks. The recycling of bricks however relies on the additives such as cement or lime in the bricks. Here, it is important to consider that processing aggregate to new bricks is an energy-intensive process. However, when reprocessing crushed bricks, compressive strength can be controlled by the additives.

Arkadia Apartments, Image © BREATHE Architects 2019

Arkadia Apartments, Image © BREATHE Architects 2019

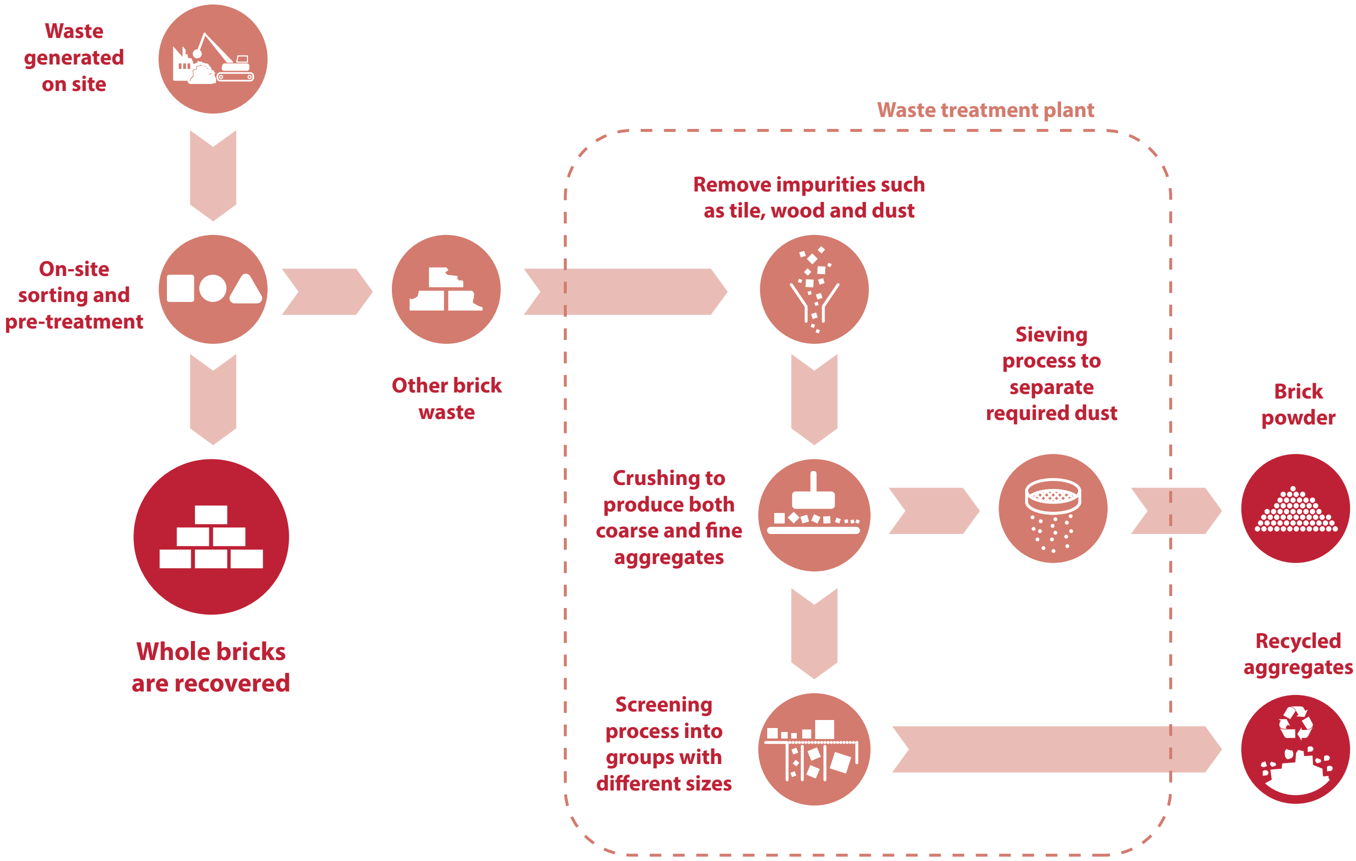


Figure 14 Value chain reused bricks

Production, process and employment effects

The value chains for reused bricks are similar to any waste materials. The reuse cycle involves gathering, sorting and preparation. Additives such as sand or cement are not necessary as the bricks can be reused in their original form. Clay bricks only need to be cleaned from mortar before they can be repurposed. However, in some cases bricks are not easily gathered as the mortar often has very strong binding capacities which does not allow for a clean extraction of and would make them break. Reuse of bricks could potentially contribute to the creation of new recycling markets and job opportunities with high-quality recycled bricks becoming more valuable with a second life. However, in many countries recycling markets do not exist yet and construction waste is disposed of in landfills.

Circularity

Closed loop manufacturing and circularity of recycled materials often depends on the mixture of the reclaimed materials and whether additives such as lime, cement or sand have been used. For example, bricks made from recycled plastic might use different plastic streams and sand or other aggregates to stabilise the brick which cannot be separated at end of life. Regular lime bricks have a lifespan of more than 200 years which makes them very durable building material.

Case Study:
Arkadia Apartments

Location: Alexandria, Australia

Architects/Developer: DKO, BREATHE Architecture

Urban Typology: Multi Residential Studio apartments

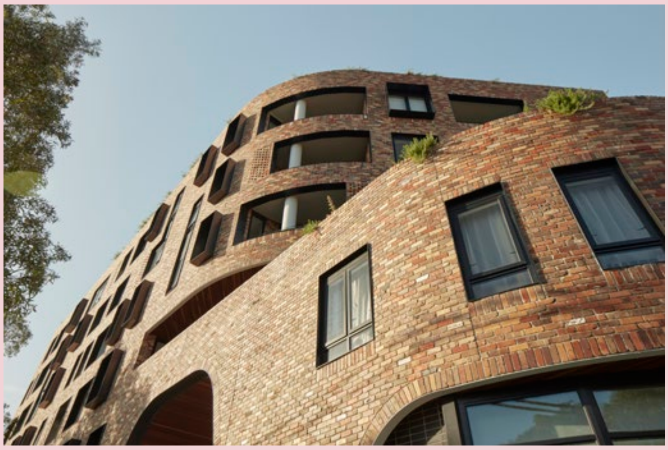
Year of construction: 2019

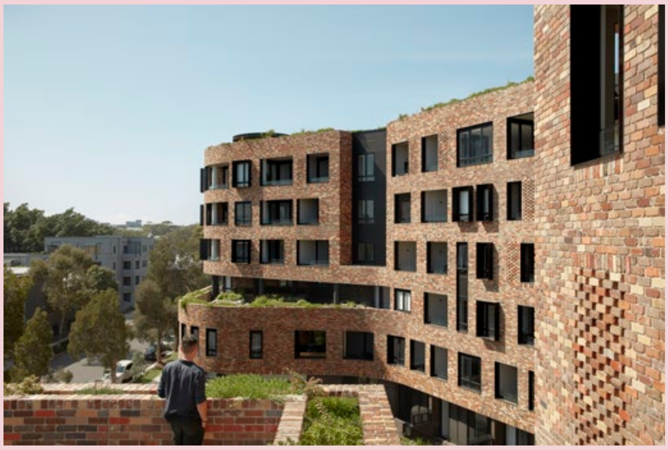
Materials: Recycled Bricks

Costs: not disclosed

At its core, Arkadia was designed to be environmentally and socially sustainable, while capturing the memory of its past. Revealing the history of the site, half a million recycled bricks paying homage to the clay quarries and brick factories that stood there in the past. Arkadia consists of four buildings, with four identities and four communities, together sharing a rooftop. Each building has its own space to come together: its own productive garden, its own lift lobby, its own address and its own community.

The Arkadia development for Defence Housing Australia occupies a 5,590 m² site in the growing inner-city suburb of Alexandria, New South Wales (NSW) and could be the largest recycled brick building in Australia. The development has been carefully integrated into the surrounding streets in a way that enhances the neighbourhood while offering a compelling model for urban living. With the recycled brick façade, the sustainable characteristics of Arkadia apartments are unmistakable. The building's structure is partly comprised of Bowral Bricks for their sharp edges and inherent character, as well as half a million multi-coloured bricks that were salvaged from multiple demolished buildings in NSW. Many of these recycled bricks were returned to their place of origin for this project, as the site was historically used for brick production.





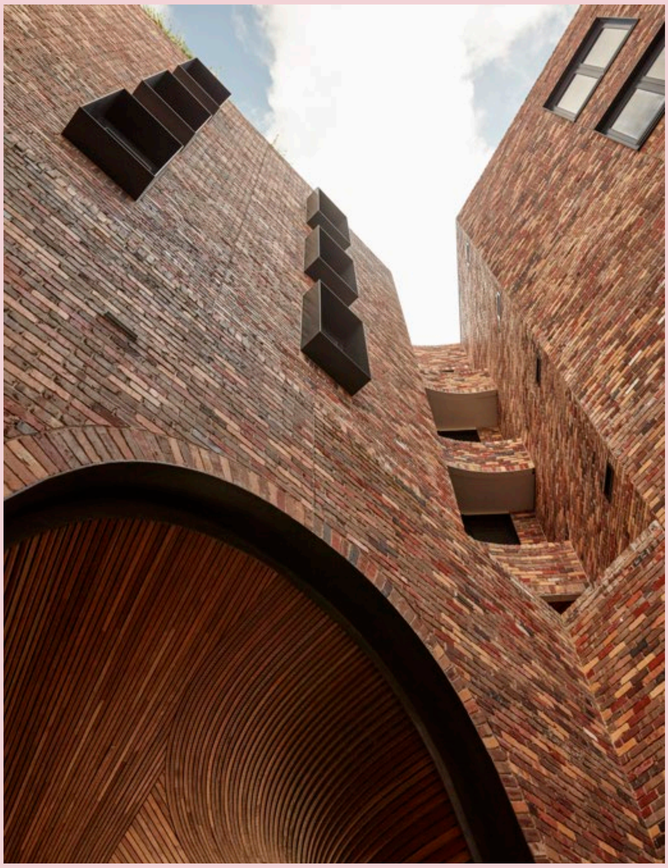


Image © BREATHE Architects 2019

Recycled Concrete

GHG and Environmental impacts

The difference between using recycled concrete and virgin materials is not as significant in terms of GHG emission mitigation as with other materials. This is mainly due to the lower structural performance of recycled materials, which needs to be compensated for by using additional reinforcements consisting of cement in most cases (Kuittinen, 2016). While the process of producing recycling-aggregates is half as carbon intense than extraction processes of gravel and sand, the production of recycling concrete using recycling aggregates, cement and other materials remains similar to the process of new concrete (Estevez, Aguado, Josa, n.d.). The cement in concrete cannot be viably separated and reused or recycled into new cement and thus carbon reductions cannot be achieved by recycling concrete.

Suitable use for construction

In most cases, recycled aggregate will be used as a subbase material, as a base for roads, parking lots, and driveways, but it can also be paired with virgin materials and reused as an aggregate in new concrete. Whenever possible, the most effective method of concrete recycling is to carry out the crushing on the construction site itself, reducing costs, pollution and emissions that would otherwise be generated when transporting material to and from a quarry or processing site. How much recycled concrete can be used depends on local norms and regulations. For example, the German guideline for structural concrete, limits the proportion of recycled aggregate up to 45%. However, material tests in Switzerland showed that high-quality concrete can be produced even with the use of more than 90% of aggregates made from scrap (ECRA, 2015). The resulting concrete maintains structural characteristics very similar to the traditional one.

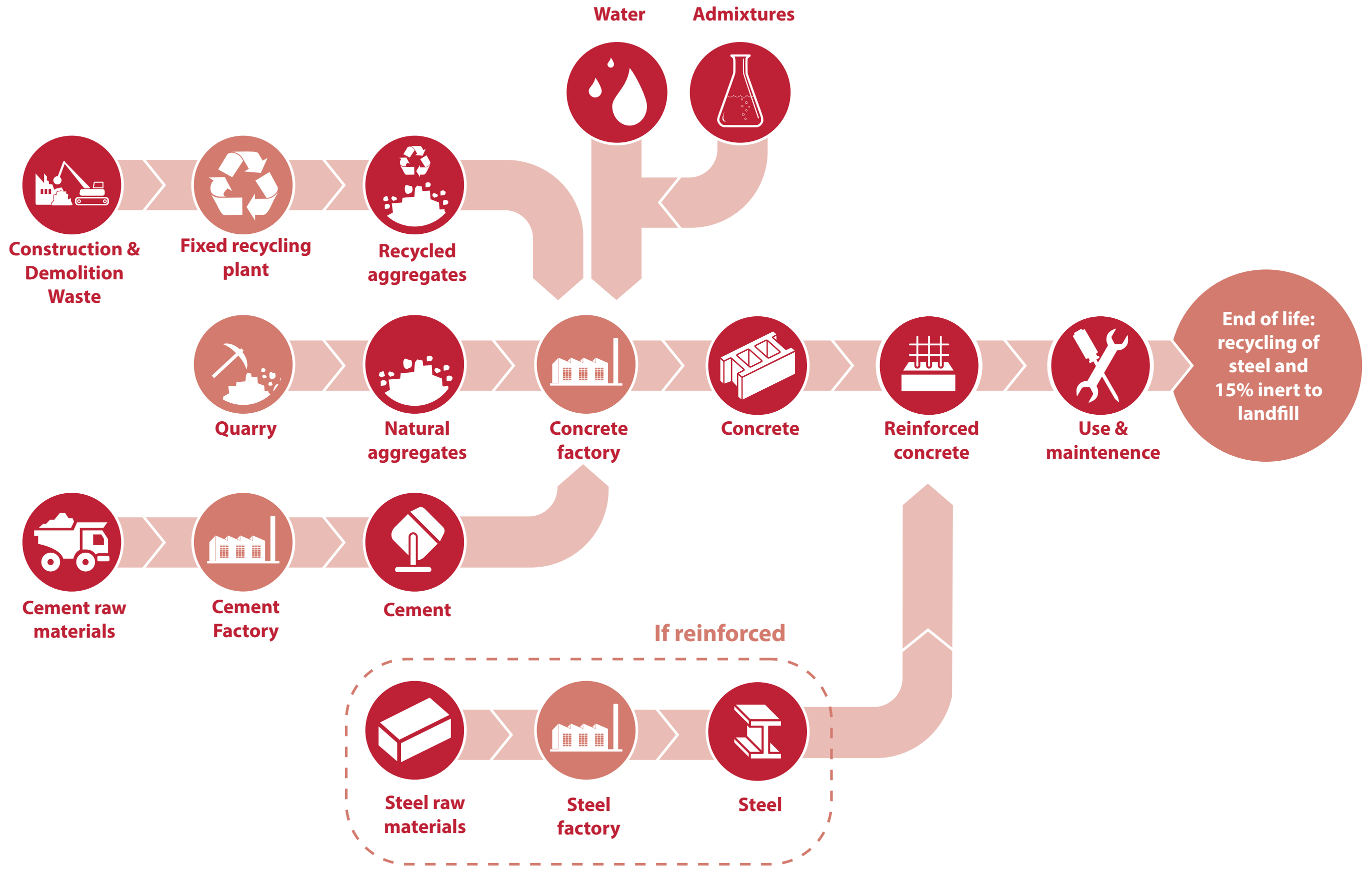


Figure 15 Value chain recycled concrete

Production, process and employment effects

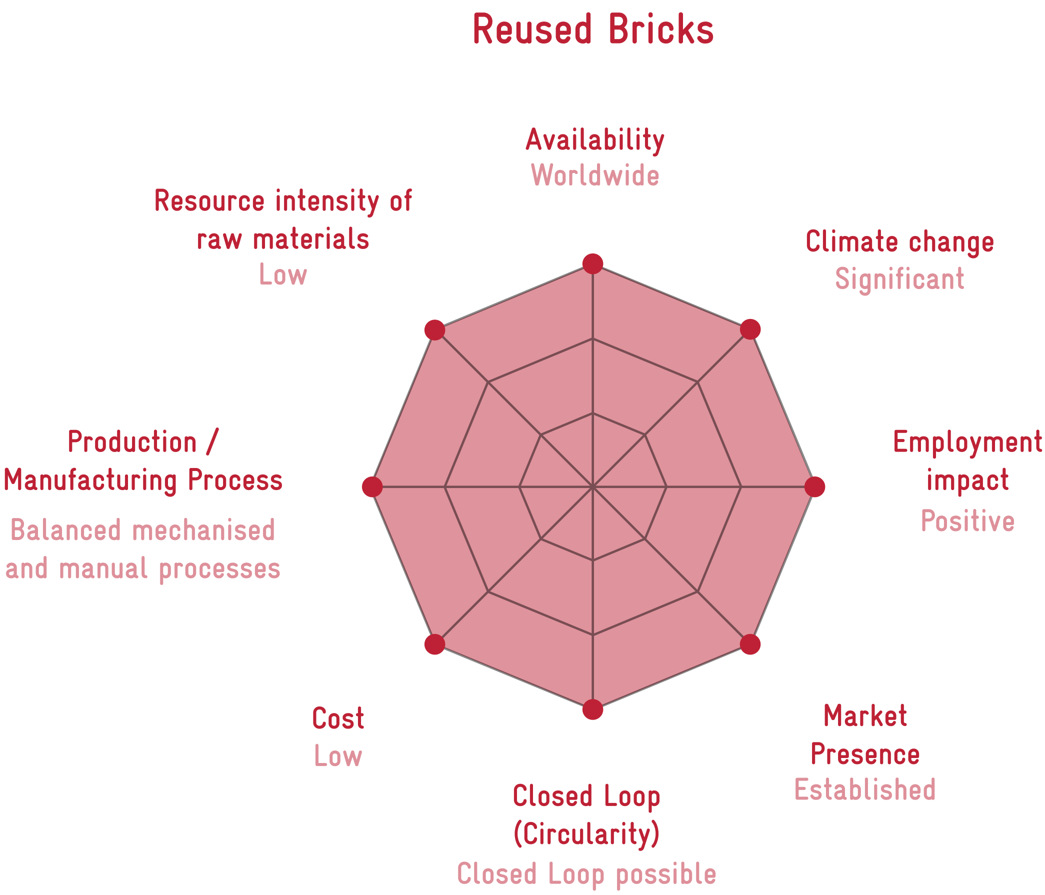
The process of recycling concrete involves the demolition of an existing building, sorting, processing and production of recycled aggregate as well as the production of concrete using recycled aggregate cement, admixtures and water (fig. xx). Today, recycled concrete is mostly used for road base, soil stabilisation or landscaping materials. In the building industry, while until recently recycled aggregate was used mostly in pilot projects only, against the backdrop of the climate emergency, is experiencing increased demand. As with all recycling material, with value increase of demolished concrete as a resource, production of recycled concrete aggregate could result in creation of new jobs within the already well-established concrete industry, also requiring new skills and interdisciplinary competencies within the sector. Especially urban areas hold potential for recycled concrete, where processes such as demolishing, production and re-use can be carried out within close distances, and a constant stream of demolition waste as a resource is provided. Here, establishment of local value chains involving both non-skilled and highly-skilled processes and labour could result in swift upscaling of the sector. With the abundance of demolished concrete as raw material, wider acceptance as a resource could result in substantial scaling up of the sector.

Circularity

Although the reuse of crushed aggregates for the production of new concrete structures is possible, it is important to mention that this does not represent a closed cycle for recycling, since the new structure cannot be made of crushed concrete without adding more cement, sand and water. In fact, studies carried out in Switzerland have shown that the use of recycled aggregates might save abiotic raw materials (gravel sand) but can increase energy consumption and greenhouse gas emissions if, due to a higher void content, more cement is used to manufacture the concrete.

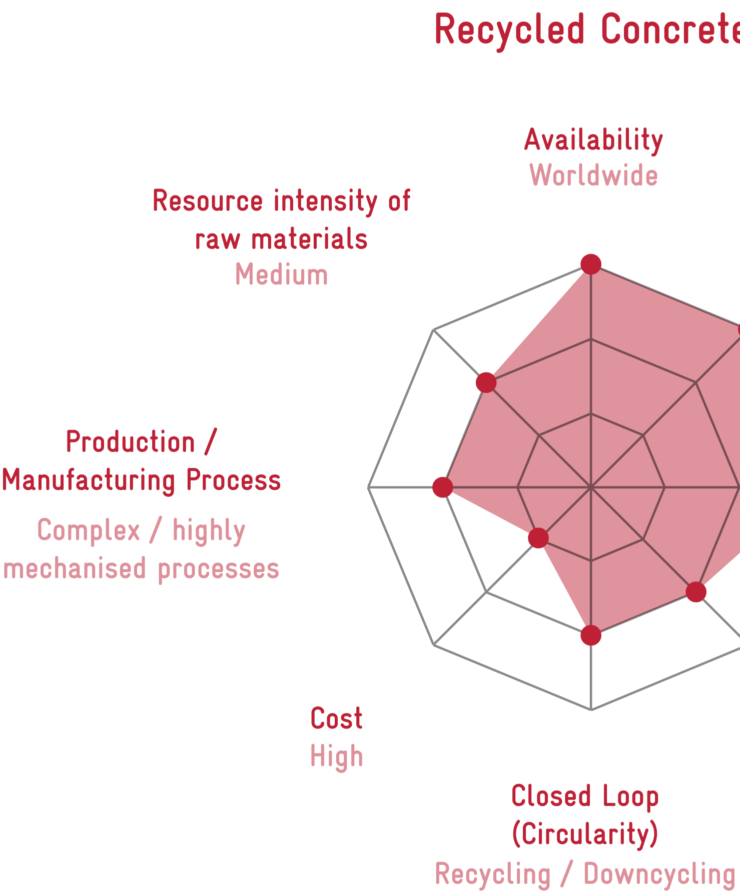
Reused Bricks Summary

Worldwide available depending on local recycling markets

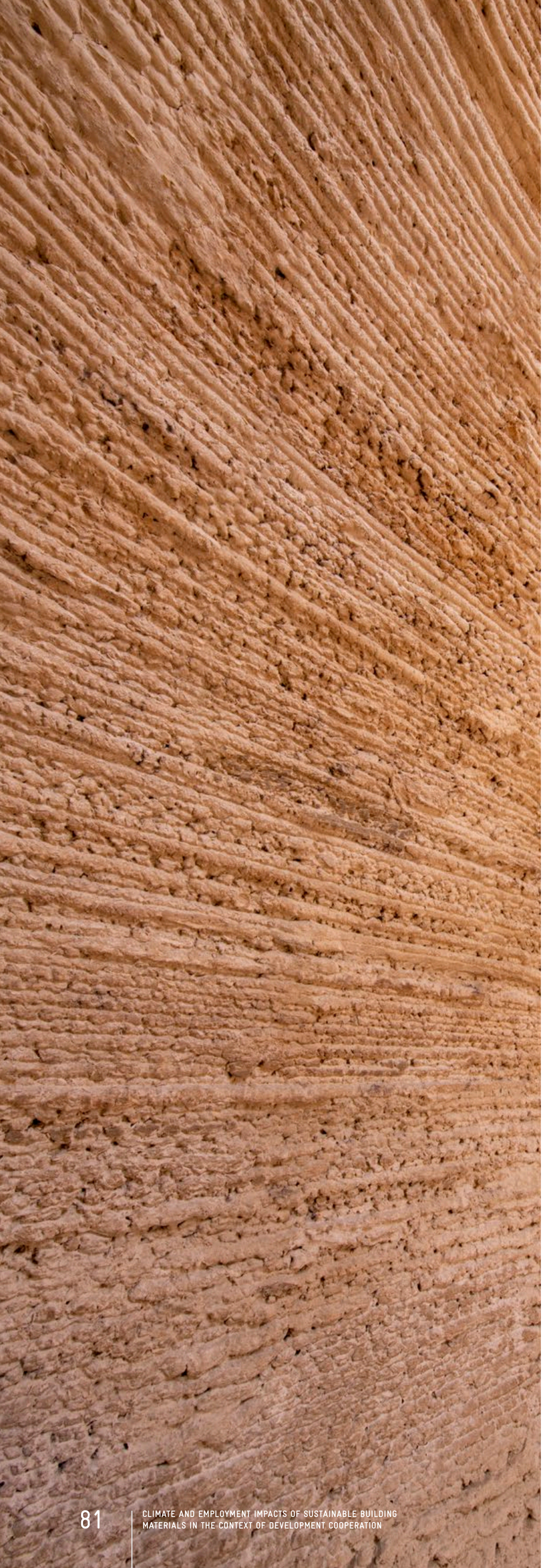


Recycled Concrete Summary

Worldwide available depending on local recycling markets



3.7 Innovations in construction methods



3D print

Material Overview

3D printing, also known as additive manufacturing, is an automated process that produces complex shape geometries from a 3D model on a layer-by-layer basis, through a series of cross-sectional slices. It has the potential to reduce material waste, decrease labour cost and fast production (Hossein et al., 2020). 3D printing for construction can be done by using a range of materials including concrete, plastic, geo-polymers and clay. While 3D printing in concrete only reduces waste and labour costs, sustainable materials such as clay have the potential of meeting material efficiency with low carbon and local materials.

3D printing technology reveals environmental potentials for sustainable construction. One attractive aspect of 3D printing for construction is the reduction of waste since the process does not require formwork and the printing can be configured to minimize material usage. By cutting down the need for raw materials, 3D printing can reduce the large environmental footprint associated with construction activities and concrete fabrication. Formwork, commonly made from timber, represents a major source of waste, since there is a limit to how many times it can be reused (Adaloudis et al., 2021). 3D printing also gives architects more freedom to experiment with novel geometries in buildings, which can be optimized in order to improve their energy efficiency or air flows, thus reducing the environmental footprint during the built environment's entire lifecycle (Rael and Fratello, 2018).

The construction industry is very labour-intensive and one of the major sources of employment in the world. The industry is experiencing low productivity with minimum technological innovations for decades. In recent times, various automation technologies including 3D printing have received increasing interests in construction. 3D printing in construction is found to be very promising to automate the construction processes and have the potential of saving laborious work, material waste, construction time, risky operation for humans, etc. (Hossein et al., 2020). However, as observed in other industries, 3D printing will also need time and retraining staff to learn how to exploit the full potential and achieve the environmental benefits of material savings (Assunçao et al., 2019; Blosch-Paidosh and Shea, 2019).

GHG and environmental impacts

The GHG emissions and environmental impacts of 3D printed houses depend largely on the material used and energy input to print as well as the transport of materials to construction location. When using concrete, GHG emission will be generated through the production process of cement as well as through emissions caused by the transport of concrete to the construction site. As concrete is used more efficiently in 3D printing than with conventional methods, emission reductions are achieved through material savings. The issue in 3D printed clay mostly rises from the use of electricity for the 3D printing operation if the clay is produced with local resources, ideally on site. A study indicates that the use of renewable energy resources and innovative material science can greatly increase the potentials (Hossain et al., 2020).

https://picryl.com/media/3d-print-concrete-building-fb842d

https://picryl.com/media/marines-engineers-conduct-a-first-of-its-kind-3d-printing-exercise-eb86f5

Tecla House, Ravenna. Video Autor: Alfredo Milano Drone views: Italdron Project by: WASP
https://www.youtube.com/watch?v=w9sXqxccRPM

Suitable use for construction

With 3D printing, each building is a prototype. This is because design of each building depends on location, functionality, materials used, and expenses. Therefore, it is difficult to standardize building projects. Printing of concrete for houses and villas has better prospect than construction of large structures. This is because 3D concrete/construction printing possess various shortcomings such as limited capacity of 3D printer for high-rise buildings, insufficient printing materials (especially for load-bearing components), low level of customization, complexity involved in the information processing from design to tangible object, etc. High rise projects are furthermore difficult to implement due to the complex placement of reinforcement in 3D printing.

Production, process and employment effects

The process of production for 3D printing is relatively short as only materials are needed on site. In the case of concrete, the production follows traditional concrete production and, in most cases, involves transport to the site. For natural raw materials such as clay, this can be reduced through sourcing clay directly on site or close by.

Even though construction works are historically very labour intensive, the impact of the labour market due to the use of 3D printing in construction has not been extensively investigated. However, 3D printing shows several advantages and disadvantages regarding labour effects. 3D construction printing will require people with special skills related to this new technology. In countries where workforces and labour are less expensive, the use of 3D printing can also have adverse effects on the labour market, leaving staff in the construction sector without employment, particular affecting low-income groups.

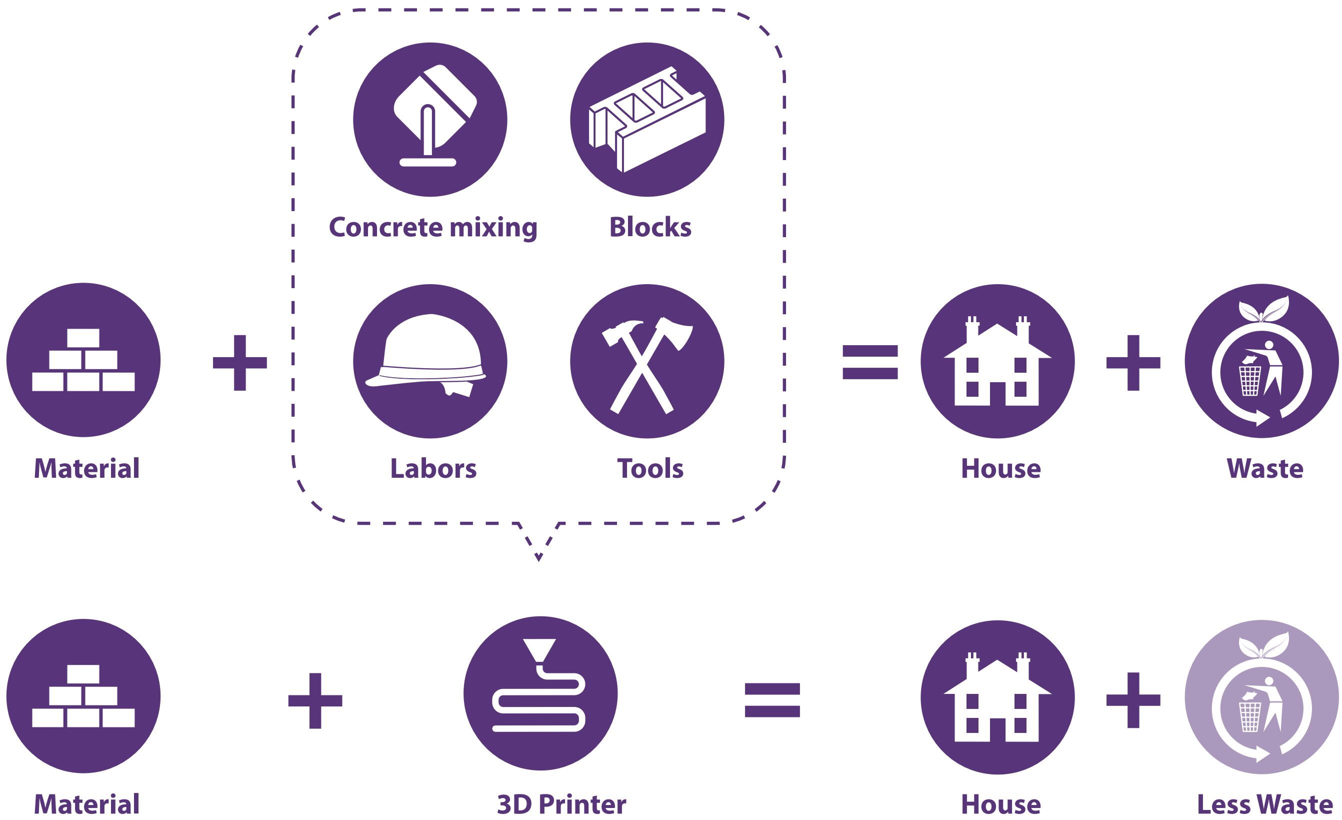


Figure 16 Traditional concrete and 3D printing process compared

Case Study:
Tecla House, Ravenna

Location: Ravenna, Italy

Architects/Developer: WASP

Urban Typology: Prototype housing

Year of construction: 2021

Materials: Raw earth

Costs: not disclosed

TECLA (which takes its name from Technology and Clay) is the first and unique fully 3D printed construction based on natural materials and made with multiple 3D printers operating at the same time. TECLA is a circular housing model that brings together research on vernacular construction practices, the study of bioclimatic principles and the use of natural and local materials. It is a nearly zero-emission project: its casing and the use of an entirely local material allows for the reduction of waste and scraps. This and the use of raw earth make TECLA a pioneering example of low-carbon housing. The composition of the earth mixture responds to local climatic conditions and the filling of the envelope is parametrically optimised to balance thermal mass, insulation and ventilation according to the climate needs. TECLA can be delivered with 200 hours of printing, 7000 machine codes (G-code), 350 12 mm layers, 150 km of extrusion, 60 cubic meters of natural materials for an average consumption of less than 6 kW (WASP, 2021).

Image © WASP 2021

Image © ICON 2019

Case Study 2: Community 3D print

Location: Tabasco, Mexico

Architects/Developer: ICON, ECHALE, New Story

Urban Typology: Residential Studio apartments

Year of construction: 2019

Materials: Lavacrete, other

Costs: not disclosed

The 500 sq ft homes were each 3D printed in around 24 hours of print time across several days by ICON, a construction technologies company, and feature final construction build out by ÉCHALE, New Story's non-profit partner in Mexico. There will be 50 total 3D printed homes in this community; two of them are already completed.

The 3D-printed homes feature two bedrooms, a living room, kitchen and bath. Co-designed with feedback from the families who will live in them, the homes have been created to meet the specific needs of the community. Resting within a seismic zone, the community and its homes were engineered above the standard safety requirements including robust foundations to ensure the homes will last for generations.

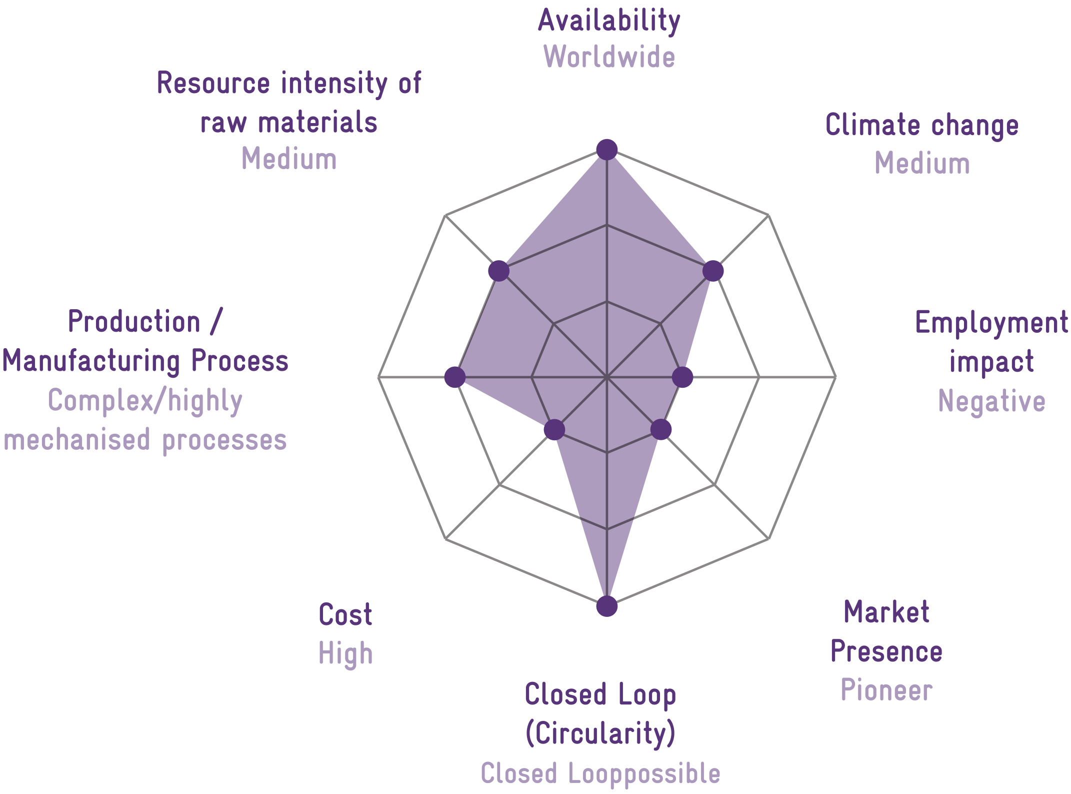
All New Story communities use a Lean Participatory Design process to involve families in the home and community planning. The community and home designs are presented to the families through our LPD process for feedback. Plans were then edited and shown to families for final buy-in. By investing into their homes, families are more likely to stay in the homes long-term, take better care of the community, and provide more meaningful feedback through the planning process.

Families in this community work in a variety of occupations and work often changes based on what is available in each season. Additionally, most of the homes the families currently live in are prone to flooding because of their proximity to the river, which overflows during the rainy season. Build out on the homes is still required for land clearing, foundations, doors, windows, and roofs. Locals are hired for all of the fit out and the numbers of individuals hired as compared to traditional construction are not expected to decrease.

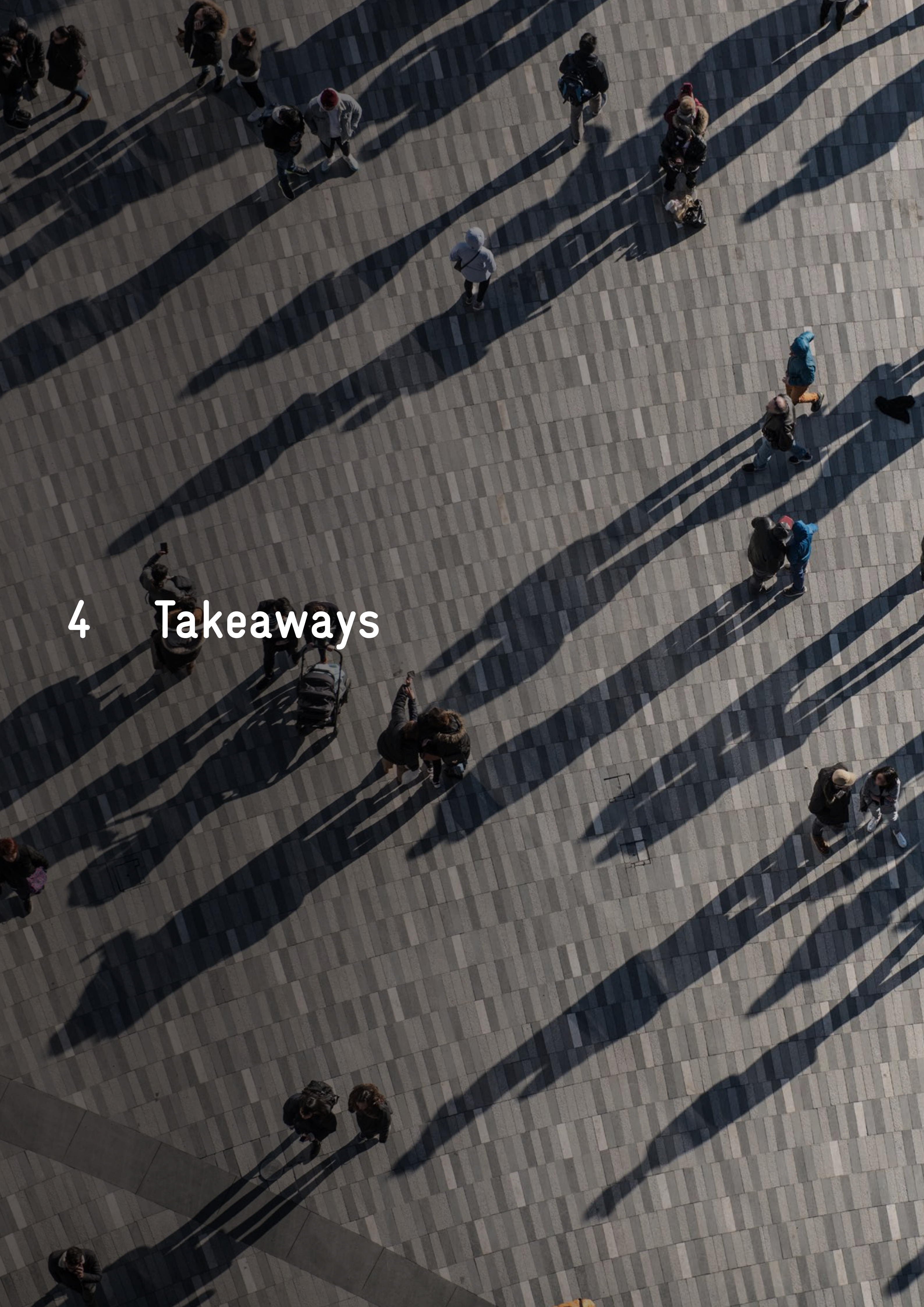
Aerated concrete Summary

Worldwide depending on used material i.e., regional concrete producing/clay soil abundance.

3D Print



4 Takeaways



Takeaways

With the pressing issue of climate change, the role of the building sector and continuous resource extraction, stakeholders in the construction sector are recognising the huge leverage of the sector in moving towards more sustainable materials and practices. Having been a niche sector since long-term, recently, sustainable building materials as an alternative or supplementary option to conventional materials are gaining more interest from architects, designers, developers, and cities. However, there is not one specific material that can solve these issues alone. Transitioning towards a more sustainable building sector requires careful assessment and selection of sustainable options depending on their suitability for the respective project typology, local or regional availability of the material, climate mitigation potential, and circularity at end-of-life of the building. In the following, five recommendations are given, that have been identified to support overcoming prevailing challenges for raising awareness and scaling-up global implementation of sustainable construction materials.

Design implications

As the case studies in this report show, materials have to be used assessed and questioned upon their suitability for each and every individual building project and typology. While some materials such as concrete with SCMs and rammed earth have a high compressive strength and can be used for load-bearing applications, materials such as straw bales are more suited for low rise buildings or interior partition walls. Because not all materials can fulfil the requirements for all building types, especially for specific urban typologies and high-rise buildings, a mix of conventional materials and sustainable materials is often necessary. In these cases, it should be aimed to minimise the amount of materials with high carbon footprints through material efficiencies, modular building or the prefabrication of elements. In many projects, it will not be feasible to completely replace conventional materials, but sustainable materials should continuously be assessed as possibility in the design process as an option for engineers and architects to choose whatever materials suits their project best under consideration of climate and environmental impacts.

Regional use and availability

Building materials such as timber, bamboo or clay might often seem as an ideal sustainable option, however, are not automatically the best choice as raw material or natural product due to their limited availability in some regions. Especially renewable raw materials such as timber, are not infinite nor sustainable when transported over great distances to the construction site. Materials can only be considered sustainable when sourced locally and from sustainable sources, not harming existing ecosystems. The same applies to waste products or agricultural by-products. A growing demand can lead to unsustainable practices where commercially unvaluable land is transformed to grow plants for natural fibres. These plants can then have a higher economic revenue but might harm the environment and biodiversity if planted in monocultures. Value chains of all sourced materials should therefore be taken into account before regionally promoting and scaling-up a specific product.

When considering suitability for materials in a geographic context, disaster risk and resilience need to be considered as well, which are often reflected or required in local building codes and regulations.

Market presence and local market opportunities

New materials such as typha boards or materials made from agricultural by-products that have not yet been used commercially can help enabling opportunities and markets for SMEs and start-ups since they do not have to compete with large established companies which could be more efficient. However, the success of new materials is also dependent on local markets and uptake of new building materials. Non established SMEs and start-ups can face problems in fluctuations of raw materials, reliabilities of subcontractors and lack of knowledge on maintenance or new technologies.

In the context of the Global South, local norms and regulations are often beneficial for introducing new materials and can offer more flexibility since local interest of communities and authorities strengthens opportunities. This means pilot projects and pioneering materials can be tested and then upscaled more easily than it often is the case in Europe or other regions of the Global North. This can further enable cooperation and global knowledge transfer. In many cases, not the existence of special regulations, but rather the lack of rigid codes allows small enterprises and private organizations to adapt building techniques to local requirements. This can lead to constructions that favour local traditional materials or vernacular construction which are not often overlooked in contemporary construction methods.

Circularity

Application of circular economy principles in the construction sector contribute to waste reductions and move towards reducing and reusing materials. Incorporating reuse elements and materials that have been recovered from an existing site into the new development can deliver substantial carbon savings and supports cost-savings in procurement of new materials. If possible, a percentage of materials (by value and quantity) should be recovered and reused on site or reused elements should be incorporated from offsite. Developments should further be designed for adaptability or flexibility to accommodate configurations and help balance the needs of the present with how those needs will change in the future.

Many sustainable building materials presented in this study such as typha, bamboo, timber or straw are made from natural materials with a high returnability to the material cycle and can in most cases be composted after end of life. However, to enable this, unnecessary toxic treatments and finishes should be avoided. Some finishes can contaminate the substrate in a way that they are no longer reusable or recyclable. This should be avoided unless finishes serve a specific purpose.

Bottlenecks and challenges

Many challenges still exist for upscaling of sustainable construction materials. Largest challenges for implementation and upscaling of sustainable construction materials are rigid or missing codes and regulations, combined with lack of awareness, information or technical knowledge. As the examples of polymer concrete, agro-based SCMs or typha show, technical challenges are not to be underestimated in getting a pioneering sustainable product to markets and meeting all regulatory requirements. Although construction practices in the Global South are in some cases not as established as in the Global North and building codes are more flexible towards new materials, the development of appropriate regulatory frameworks often takes a long time and hampers large-scale implementation. Often, builders stay attached to well-known techniques and materials, which in most cases is steel and concrete.

Another barrier for implementation is lack of knowledge on how to use natural materials appropriately and plan for maintenance and repair of materials and building elements. This also includes using materials characteristic behaviour beneficially for example to build on structural (rammed earth) or tensile strength (bamboo). Thereby, material properties define the possible designs to work with for a development.

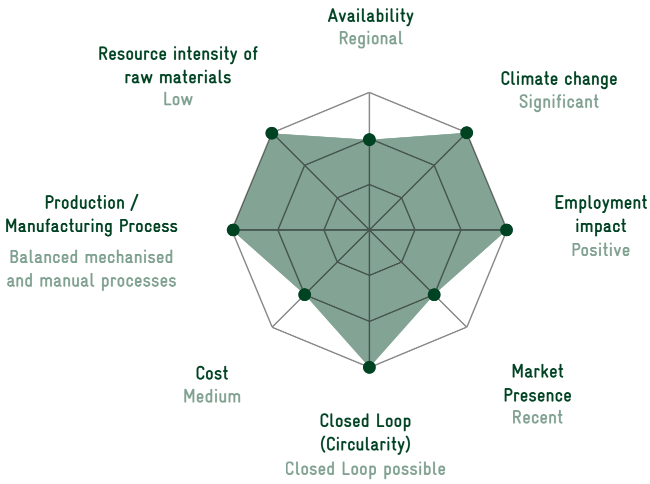
Globally, to date, there is still a lack of detailed data on material use, climate impacts and employment effects resulting from sustainable construction material. The lack of information on embodied energy and CO_2 emissions of different types of building materials is a big challenge for architects to design buildings with low-environmental impact. Even if not all materials can be sourced sustainably or designed for composting or reuse, it is important to contribute to data collection.

5 Overview of Materials

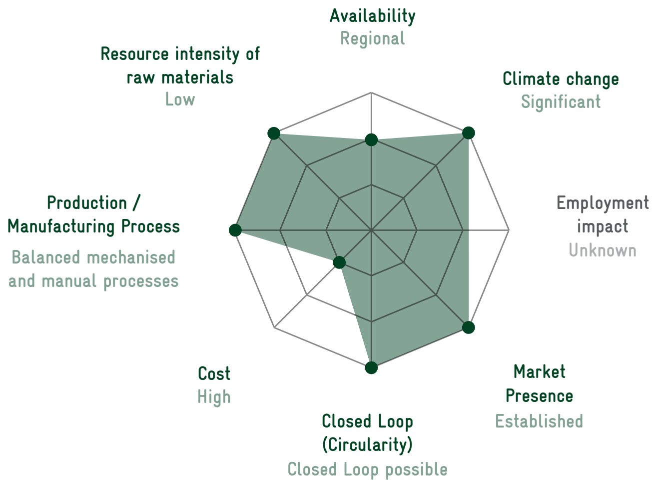
Material		Availability	Climate Impact	Employment impact
"Renewable/ Organic Materials"	Mass Timber (CLT, NLT, Gulam)	Forests can be found worldwide but depending on their regional distribution (boreal, temperate, tropical rainforest). Countries with the largest forested area include Russia, Canada, Brazil, China, and the United States.	Dry wood is about 50% carbon by weight and so mass timber buildings store considerable amounts of carbon over their lifespan	As timber has been used for centuries as building material, it has an established market presence in many regions worldwide. Startups exist for very specific applications of timber for construction such as glue less joints.
	Bamboo	Bamboo grows in a "belt" running through tropical, subtropical and temperate climates around the globe. It grows naturally in all the continents except Europe. Generally, bamboos prefer the tropical or sub-tropical climates.	As a naturally growing plant, bamboo building elements can sequester carbon over their lifespan. However, the overall CO_2 balance depends on the usage and degree of processing and transport distances.	Social benefits of employing less-educated laborers in the bamboo industry can be gained, as the skills needed for processing bamboo materials is low.
	Typha	Typha is distributed worldwide ranging from temperate climate zone to tropical regions, where they can be found in a variety of wetland habitats.	Typha crops function as a carbon sink as they are growing as well as to the bonding of CO_2 when typha is grown on fen soils. Typha also functions as nutrient trap, as well as erosion barrier for water retention.	Typha offers many positive impacts on local employment and regional product supply. Typha can contribute to the creation of employment in structurally weak regions through income opportunities for small and medium-sized companies and agriculture.
	(Rice) Straw Bale	Agricultural plants such as cereals (i.e. wheat, rice, barley, oats, rye), corn, cotton, etc. are globally grown for the crop. China, India and the USA appear to be at the present the major producing countries of straw residues (mainly wheat and rice straw).	Straw stores sixty times more carbon than is used to grow, bale and transport to building sites in the same region. A straw bale is approximately 40% carbon by weight. It naturally sequesters carbon both in grain stalk itself and by storing carbon into the soil.	Examples show, that straw bale constructions have a very positive impact on local communities and gender equity. Projects of straw bale construction further enhanced community capacity building through increasing skills and income
Clay	Rammed earth	As other forms of earthen construction, rammed earth has been used for centuries in many regions of the world. Major centres of rammed earth construction include North Africa, Australasia, regions of North and South America, China and Europe, including France, Germany and Spain.	With no firing process, no kilns, zero toxic emissions, rammed earth has around 70% reduction in embodied energy compared to bricks and a high thermal mass (around 9.3 kg CO_2eq/m^3). However, the embodied energy is also dependent on stabilisers (lime, cement).	Although raw earth construction requires good knowledge and understanding of soil types, all the earth construction techniques do not require specialised manpower, which allows anyone to build a house with resource to simple tools
	Unfired Clay brick	Illite used for clay bricks mostly, is one of the most abundant clay minerals in sediments and rocks, and the major constituent of many brickmaking clays all over the world. Depending on regional clay soil abundance.	Depending on raw material extraction, additives, manual manufacturing (casting), and delivery of material to the building site, unfired earth bricks emit only around 93.6 kg CO_2eq/m^3.	
Supplemental Cementitious Materials	Industrial-based SCM Agro-based SCMs	Possibly worldwide but depending on regionally used agro/bio elements.	Partial replacement of conventional concrete elements through cement alternatives could beneficially affect the emission reduction of the overall project. However, carbon emission savings depend largely on the type cementitious material.	Production of agro-based SCMs could have positive impacts on local value chains, as it is a waste product which is not commercially used yet. Since rice or other agricultural by-products can be used to produce SCMs, the product is not locally or regionally restricted
Alternative Concretes	Polymer Concrete	Possibly worldwide but depending on regionally used sands and binders.	As polymer concretes are still remains on experimental stages, a lack of data on carbon savings exists. However, studies show CO_2 reductions of up to 58% compared to conventional concrete.	The local extraction of raw materials (desert sand) as well as setting up factories creates new jobs. Necessary raw materials can create new demand on recycling market which is often largely run by informal waste pickers. To work in the manufactoring process, staff needs to be skilled to a certain degree.
Recycled Materials	Reused Bricks	Regionally not restricted and technically available worldwide. However, they are bound to local recycling markets.	The use of reused clay bricks instead of new bricks can result in considerable environmental benefits. However, this depends on the transport disctance, ideally bricks should be used locally.	The development of recycling infrastructures could open up new markets for undervalued waste materials and could create local employment opportunities.
	Recyled Concrete	Regionally not restricted and technically available worldwide. However, they are bound to local recycling markets.	Using recycled concrete is thought not to be significant in terms of GHG emission mitigation. This is mainly due to the lower structural performance of recycled materials, which needs to be compensated for by using additional reinforcements consisting of cement in most cases.	
Sustainable Construction Methods	3D printed Clay/ Concrete	Worldwide depending on used material i.e., regional concrete producing/clay soil abundance.	GHG emissions and environmental impacts of 3D printed houses depend on the material used and energy input to print as well as the transport of materials to construction location.	The impact of the labour market due to the use of 3D printing in construction has not been extensively investigated, however, people with special skills related to this new technology will be required. In countries where workforces and labour are less expensive, the use of 3D printing bears the risk of leaving staff in the construction sector without employment.

Market Presence	Closed Loop (Circularity)	Cost	"Production/ Manufacturing Process"
CLT panel products have developed to the stage where they can be considered as economic and more sustainable alternatives to traditional materials.	Dependent on treatment or glue, timber can potentially be shredded and returned to the material cycle after end of life by composting. Not yet common practice.	Depending on local markets and degree of processing.	Depeding on the timber product produced, the processing onvoles simple to comlex processing. After primary processing, the raw materials are then transported to produce engineered woods manufacturing such as GLULAM or CLT. To manufacture engineered woods, skilled to highly skilled labour is necessary as well as heavy machinery.
Bamboo has a long- and well-established tradition for being used as a construction material throughout the tropical and sub-tropical regions of the world	Dependent on treatment or glue, bamboo can potentially be shredded and returned to the material cycle after end of life by composting. Not yet common practice.	Depending on local markets and degree of processing.	Bamboo plywood is nowadays one of the most typical and often found industrial products of bamboo. Like many other industrial bamboo board-like products, bamboo plywood is processed similar to the process of engineered wood products.
Typha has not yet been used on larger scales and remains in a pioneering phase.	High returnability to the material cycle and can in most cases be composted after end of life (»Cradle to Cradle«). For typha blocks, only non toxic magnesite adhesives are added which make composting possible.	Typha is also considered to be an affordable material with one ton of dry typha reed at about 5000 CFA (7€) per ton.	The manufacturing of Typha boards or paneks involves balanced mechanised and manual processes mostly consisting of harvesting, sorting, mixing and moulding typha leaves and stems.
Straw bale construction has been used for centuries and has recently gained more interest in modern applications.	Being 100% biodegradable, when straw buildings become obsolete and need to be demolished, its walls can decompose into the soil without major problems. However, plaster and finishes directly on the walls need to be natural materials too in order to be composted.	As a waste product, easily available and economically viable, straw bale is a low-cost material. The building method is straightforward and people without previous building experience can participate in the design and construction, thereby saving on labour costs.	The manufacturing of straw bales for compcated straw bale construction involves preparing the straw, compaction and other processes related to structural frames if the straw is used for infill. The building method is straightforward so people without previous building experience can participate in the design and construction,
Rammed earth has a long and continued history throughout many regions of the world and has recently experienced a modern revival. Over the past fifty years a number of standards and national reference documents have been published.	The circularity of rammed earth and unfired clay bricks depends on stabilizing agents and additives like cement and lime. Without additives, buildings constructed from rammed earth can be deconstructed using manual tools like axes and the material can degrade back into nature as soil.	Material costs are relatively low for raw earth. However, rammed earth construction is labour intense.	The production process involves soil extraction and treatment, mixing, loading the formwork and ramming. The technique does not require a lot of skills and can be practiced by local and unsilled to skilled workforce.
In today's world, brick is considered as one of the most sought after materials used in the construction of various civil engineering structures. The use of bricks is ganing more interest for construction recently.		Low material and production costs but still often more expensive than conventional bricks as they can be produced cheaper due to economies of scale.	Clay bricks are being made using suitable soil, additives such as straw, sand or cement and water. The bricks are then going through a drying process for various days, depending on the additives and level of humidity. Raw earth construction requires good knowledge and understanding of soil types in order to obtain the appropriate soil mixture.
The use of SCMs currently remains on experimental stage, with current research exploring compressive strength of concrete using industrial/agro-based cementitious alternatives.	Recycling/Downcycling. At present there are no studies on the behavior of recycled concrete using SCMs. It can be assumed that SCM concrete would behave similarly to normal concrete which means it could either be crushed and used as aggregates or reused with new SCMs and cement.	SCMs made from industrial- and agricultural by-products could be produced at relatively los costs as they are made form waste products which are not commercially used yet. However in the experimental phase they remain at higher costs than concentional cement.	Production of SCMs depends on the source of industrial- or agricultural by-products and ususally either are produced through burning processes or are arrise as by-products through industrial processes 8for example in the steel industry).
The use of Polymer Concretes currently remains on pioneer stage. While the certification for construction is already granted in various African countries, the approval for polymer concrete as a building material in other continents is still in its infancy.	Although the material components such as the binder or Styrofoam for insulation cannot easily be dismantled and recycled, the bricks can be reused many times replacing the use of virgin materials and energy use for manufacturing processes.	Low material and production costs but still often more expensive than conventional bricks as they can be produced cheaper due to economies of scale.	For polymer concrete, various raw materials can be used ranging from desert sand, silica sand or foundry sand making use of local resources to shorten transport of raw materials. These materials are then combined with a binder.
Using bricks is an establised technique, reuse/ deconstructing market not yet established in most countries	Closed Loop possible, bricks can be reused multiple times	Although recycled materials have been gaining more interest over the last years, recycling markets are not established in many places which often results in higher prices of these materials.	The value chains for reused bricks are similar for many waste materials. The production involves a gathering process, sorting process, preparation process and production.
Recycled and crushed concrete has been used for other purposes than construction mainly. Reuse with new cement not yet established.	Recycling with new cement or downcycling. Still mostly used as infill and road underbuilds.		Recycling concrete involves complex or highly mechanised processes. It involves the demolition of existing buildings, sorting, processing and production of recycling aggregate as well as the production of concrete using recycled aggregate cement, admixtures and water.
3D printing remains in the pioneer phase. Because design of each building depends on location, functionality, materials used, and expenses, it is difficult to standardise building projects	The circularity of 3D printed houses depends largely on the material used, whle clay can degrade back to soil (if no additives are used), concrete can be crushed and recycled.	As 3D print requires highly complex printers, machines and technically well trained staff, this construction method is still cost intensive.	For 3D construction, only materials and printer are needed on site. In the case of concrete, the production follows traditional concrete production. Natural raw materials such as clay can be used directly on site or sourced close by.

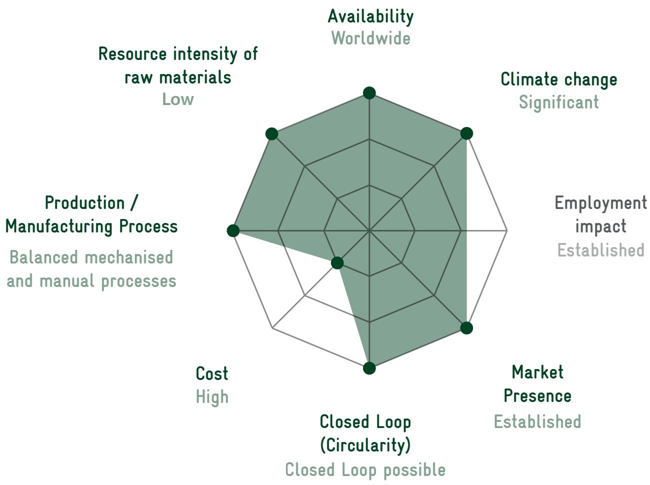
Thypha



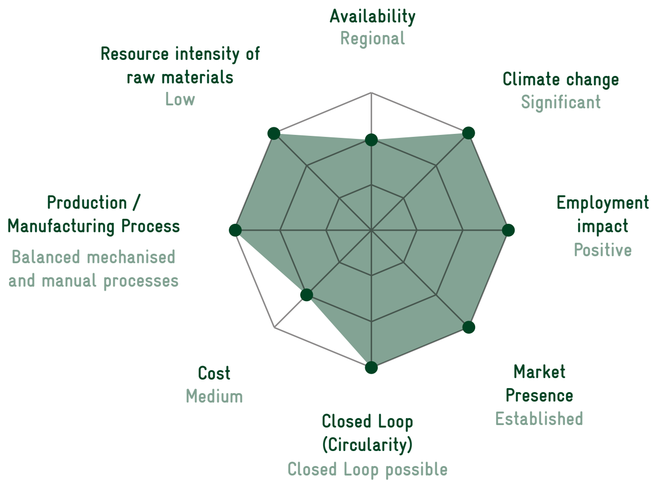
Bamboo



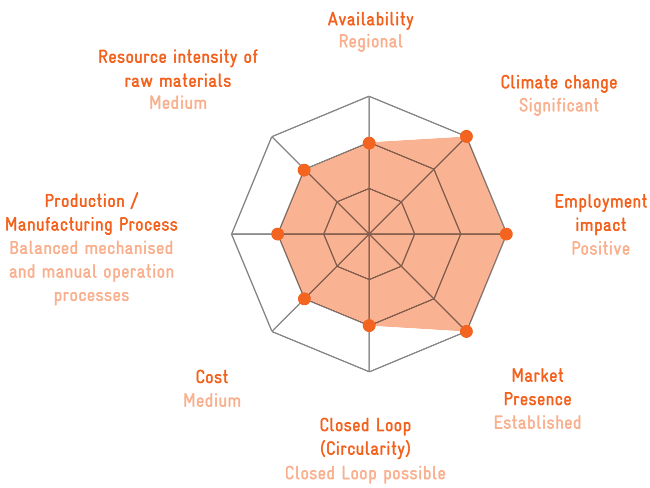
Mass Timber (CLT, NLT, Gulam)



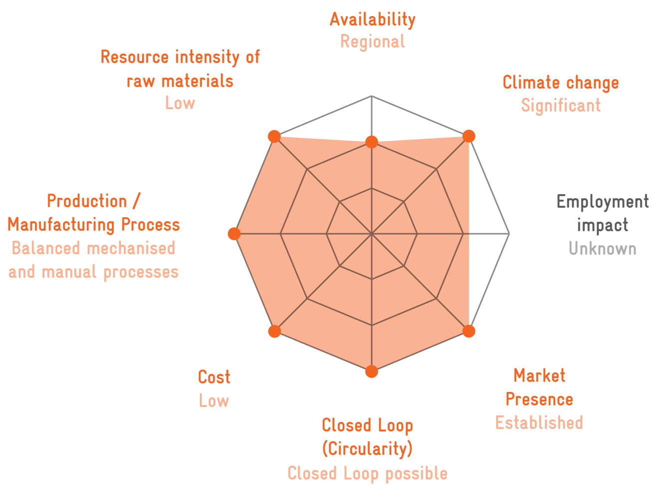
(Rice) Straw Bale



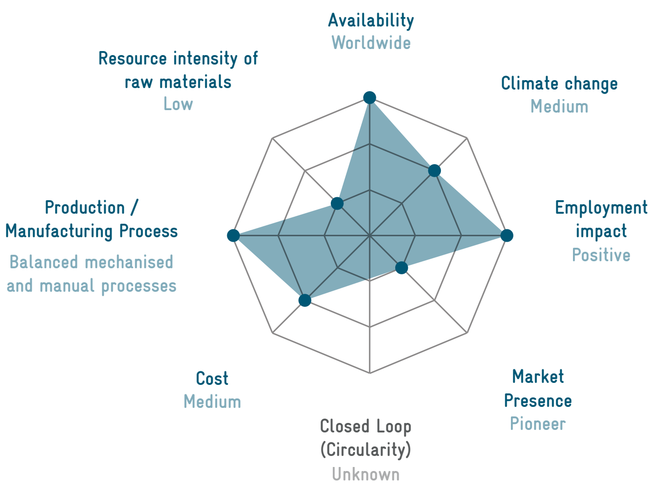
Unfired Clay bricks



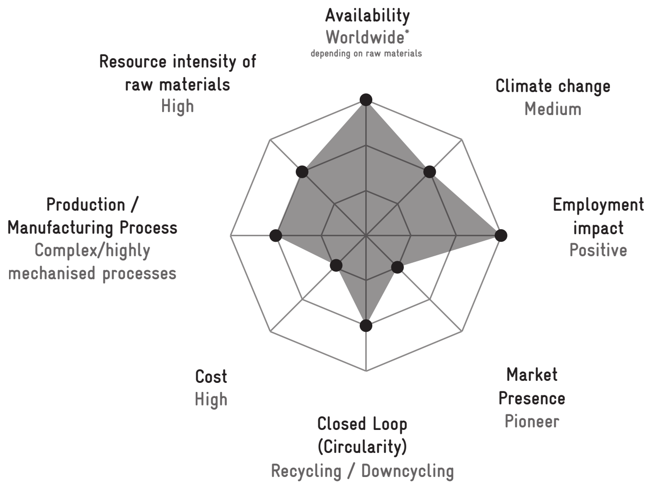
Rammed earth



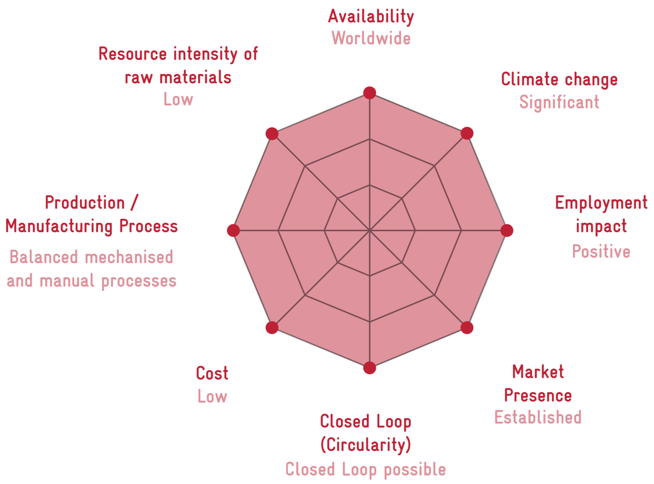
Supplemental Cementitious Materials



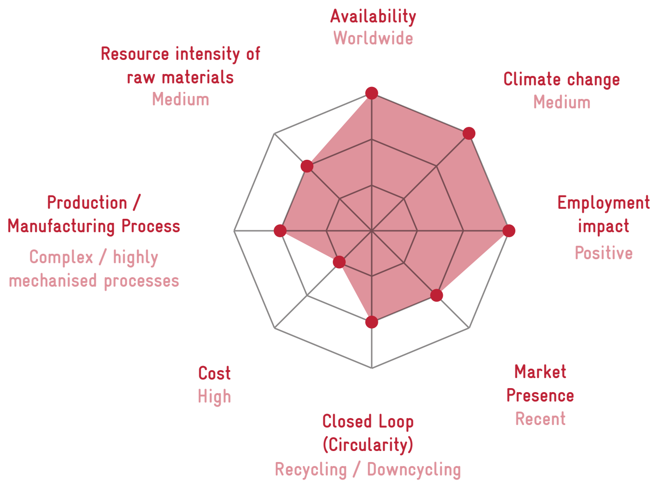
Polymer Concrete



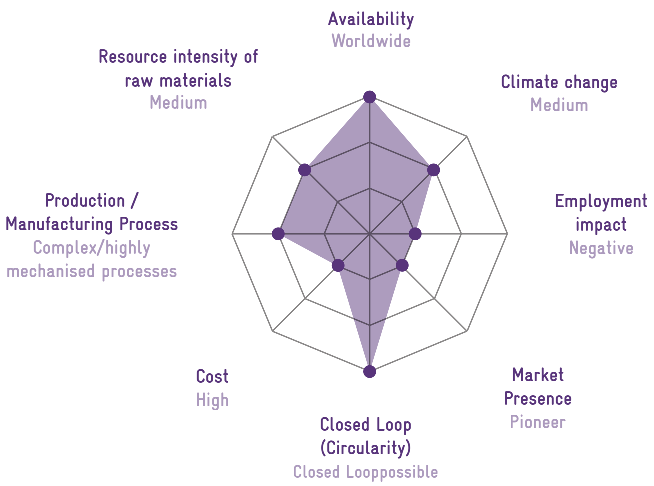
Reused Bricks



Recycled Concrete



3D Print



6 Sources

6.1 General Sources

UN Environment (2017). Towards a zero-emission, efficient, and resilient buildings and construction sector. Global Status Report 2017

WGBC - World Green Building Council (2019). Bringing Embodied Carbon Upfront. URL: https://www.worldgbc.org/embodied-carbon (Assessed on 17/09/2021)

6.2 Material Sources

Typha

Dione, E. (2019). #8 The use of typha in Senegal, interview with Ernest Dione in Construction21 international. URL: https://www.construction21.org/articles/h/8-the-use-of-typha-in-senegal-interview-with-ernest-dione.html (last accessed 16.08.2021)

Krus, M. (n.d.) Innovative construction with cattail as raw material. Fraunhofer Institute for building physics. IPB.

Krus, M., Fleck, T. (2013). The cattail – an insulating material with real promise. Research in focus May 2013

Martin Krus, Werner Theuerkorn, Theo Großkinsky, Georgi Georgiev (2014). Technology: A New Load-Bearing Insulation Material – Typha Panels. GREEN, 01-02/2014. https://inspiration.detail.de/technology-a-new-load-bearing-insulation-material-typha-panels-108956.html

CRA Terre (2014). Projet PNEEB / TYPHA « Transfert de technologie: Projet de production de matériaux d'isolation hermique à base de Typha. » RAPPORT TECHNIQUE Identification du contexte sénégalais.

Bamboo

Heilman, P.E., Xie, F.G. (1993). Influence of nitrogen on growth and productivity of short-rotation Populus trichocarpa X Populus deltoides hybrids. Canadian journal of forest research (Canada). ISSN: 0045-5067

Kaminski, S., Trujillo, D., Lawrence, A., (2016). Technical Note Series: Structural Use of Bamboo. Technical Note 1: Introduction to Bamboo. In: Structural Engineer, August 2016.

Lakshmipathy, K., Sanathakumar, P.T., (1980). The Planting, the Flora of West Tropical Africa, vol. II. Millibark, London, pp. 251–253.

Lei Gu, L., Zhou, Y., Mei, T., Zhou, G., Xu, L. (2019). Carbon Footprint Analysis of Bamboo Scrimber Flooring—Implications for Carbon Sequestration of Bamboo Forests and Its Products. Forests 2019, 10, 51; doi:10.3390/f10010051

Liese, W. (1985). Bamboos – Biology, silvics, properties, utilization (eng. text by B.Jackson). Deustche Gesellschaft für Technische Zusammenarbeit (DTZ) GmbH, Eschborn (Kennan, 2015).

Mathew, P.M. (1998). The Bamboo Economy of Kerala, India: an Analysis of the Production-to-Consumption Systems. INBAR Working Paper No. 12.

McClure, F.A. (1966). The Bamboos, a fresh Perspective. Harvard University Press, Cambridge, Massachusetts

Rana, P. Mukul, S. Sohel, Md.; Chowdhury, S. (2010) Economics and Employment Generation of Bamboo-Based Enterprises: A Case Study from Eastern Bangladesh. Small-scale Forestry (2010) 9:41-51.

Swamy, C., (2011). Employment Generation by Bamboo Resource Development and its impact on rural Communities. International Journal of Rural Studies (IJRS), vol. 18 no. 1 Apr 2011. ISSN 1023–2001.

Van der Lugt, P. (2008). Design interventions for stimulating bamboo commercialization - Dutch design meets bamboo as a replicable model.

Van der Lugt, P., Vogtländer, J.G. (2015). The Environmental Impacts of Industrial Bamboo Products. Life Cycle Assessment and Carbon sequestration. Technical Report Nr.35. INBAR.

Mass Timber

Brandner, R., Föatscher, G., Ringhofer, A., Schickhofer, G., Thiel, A. (2016). Cross-laminated Timber (CLT) Overview and Development. European Journal of Wood and Wood Products 74.3 (2016): 331-351.

Churkina, G., Organschi, A., Reyer, C.P.O., Ruff, A., Vinke, K., Liu, Z., Reck, B.K., Graedel, T.E., Schellnhuber, H.J., 2020. Buildings as a global carbon sink. Nat. Sustain. 1–8. https://doi.org/10.1038/s41893-019-0462-4.

Harte, A.M. (2017). Mass timber – the emergence of a modern construction material. Journal of Structural Integrity and Maintenance, 2:3, 121-132, DOI: 10.1080/24705314.2017.1354156

Hill, C.A.S., (2019). The environmental consequences concerning the use of timber in the built environment. Front. Built Environ. 5 https://doi.org/10.3389/fbuil.2019.00129.

Himes, A., Busby, G. (2020). Wood buildings as a climate solution. Developments in the Built Environment 4 (2020) 100030.

Sathre & O'Connor (2010). A Synthesis of Research on Wood Products and Greenhouse gas impacts. 2nd Version. Vancouver, B.C. FP Innovations. Technical Report Tr-19R.

Monsh University. https://www.monash.edu/mada/research/crc-p-lca-of-mass-timber-construction

Straw Bale

Adam, F.M., Ali, S.A. (2015). Suitability of using straw bale as a building material in Sudan. UKIERI Concrete Congress - Concrete Research Driving Profit and Sustainability.

Atkinson, C., (2008). Energy Assessment of a Straw Bale Building, University of East London.

Barbara Jones, Building with Straw Bales: A practical guide for the UK and Ireland, Green Books, 2002.

Builders without Borders (2015). Nepal Housing reconstruction programme. Straw Bale Construction, One-Storey. SB. 1.1

Garas G., Allam M. and El Dessuky R. (2009). Straw bale construction as an economic environmental building alternative- a case study. ARPN Journal of Engineering and Applied Sciences. Vol. 4, No. 9, November 2009.

Gonzales, A.d. (2015). 21 - Assessment of the energy and carbon embodied in straw and clay masonry blocks. In: Eco-Efficient Masonry Bricks and Blocks Design, Properties and Durability 2015, Pages 461-480.

Mutani, G., Azzolino, C., Macrì, M., Mancuso, S. (2020). Straw Buildings: A Good Compromise between Environmental Sustainability and Energy-Economic Savings. Appl. Sci. 2020, 10, 2858; doi:10.3390/app10082858.

Nadav, M. (1993). "Building with Straw Bale" URL:buildinggreen.com.

Re-Alliance (2021). https://www.re-alliance.org/nepal-strawbale

Steen A. S., Steen B., Bainbridge D. And Eisenberg D. (1994). The Straw Bale House, Chelsea Green Publishing Company.

Walker, P., Thomson, A., Maskell, D. (2020) 9 - Straw bale construction. In: Nonconventional and Vernacular Construction Materials (Second Edition). Woodhead Publishing Series in Civil and Structural Engineering 2020, Pages 189-216

Unfired Clay Bricks

Bowen, T. (2017). A best practice manual for using compressed earth blocks in sustainable home. Construction in Indian country.

Bown, A.R. (2007). Whole life performance of clay brickwork masonry. Leeds Metropolitan University.

Brick Development Association (2009). Brick Bulletin- Spring 2009 edition. https://www.brick.org.uk/publications/brick-bulletin.html

Christoforou, E., Kylili, A., Fokaides, P.A., Ioannou, I., 2016. Cradle to site life cycle assessment (LCA) of adobe bricks. J. Clean. Prod. 112 (1), 443e452. https://doi.org/10.1016/j.jclepro.2015.09.016.

Cid-Falceto, J., Mazarrón, F.R., Cañas, I. (2012). Assessment of compressed earth blocks made in Spain: International durability tests. Construction and Building Materials 37:738–745. DOI:10.1016/j.conbuildmat.2012.08.019

Dabaieh, M., Heinonen, J., El-Mahdy, D., Hassan, D.M. (2020). A comparative study of life cycle carbon emissions and embodied energy between sun-dried bricks and fired clay bricks. Journal of Cleaner Production 275 (2020) 122998.

Fayomi, G.U., Mini, S.E., Fayomi, O.S.I. (2019). Perspectives on environmental CO_2 emission and energy factor in Cement Industry. IOP Conf. Ser.: Earth Environ. Sci. 331 012035

Gursel, A. P., Maryman, H., Ostertag, C. (2016) A life lycle approach to environmental, mechanical, and durability properties of "green" concrete mixes with rice husk ash. Journal of Cleaner Production, 112(1), 823 836. doi: https://doi.org/10.1016/j.jclepro.2015.06.029 Gursel, A. P., Masanet, E., Horvath, A., Stadel, A. (2014) Life

Kinuthia, J.M.; Oti, J.E. (2012). Designed non-fired clay mixes for sustainable and low carbon use. Appl. Clay Sci. 2012, 59–60, 131–139.

Kinuthia, J.M.; Oti, J.E. Designed non-fired clay mixes for sustainable and low carbon use. Appl. Clay Sci. 2012, 59–60, 131–139

Kishore, R., Bhikshma, V., Prakash, P. J. (2011) Study on strength characteristics of high strength rice husk ash concrete. Procedia Engineering 14, 2666 2672. doi; https://doi.org/10.1016/j.proeng.2011.07.335

Morton T., (2008). Earth Masonry, Design and Construction Guidelines, HIS BRE Press, Bracknell, Berkshire UK.

Murmu, A.L., Patel, A. (2018). Towards sustainable bricks production: An overview. Construction and Building Materials. Volume 165, 20 March 2018, Pages 112-125. https://doi.org/10.1016/j.conbuildmat.2018.01.038

Oti, J.E. (2010). The Development of Unfired Clay Building Materials for Sustainable Building Construction

Rammed Earth

Akbarnezhad, A., Xiao, J., (2017). Estimation and Minimization of Embodied Carbon of Buildings: A Review. Buildings 2017, 7, 5; doi:10.3390/buildings7010005

Maniatidis, V., Walker,P., (2003). A Review of Rammed Earth Construction for DTi Partners in Innovation Project 'Developing Rammed Earth for UK Housing'.

Morel, J.C., Charef, R., (2019). What are the barriers affecting the use of earth as a modern construction material in the context of circular economy? IOP Conf. Ser.: Earth Environ. Sci. 225 012053

Reddy, B.V.V.; Kumar, P.P. Embodied energy in cement stabilised rammed earth walls. Energy Build. 2010, 42, 380–385.

Polymer Concrete

Alhazmi, H.; Shah, S.A.R.;Anwar, M.K.; Raza, A.; Ullah, M.K.; Iqbal, F. Utilization of Polymer Concrete Composites for a Circular Economy: A Comparative Review for Assessment of Recycling and Waste Utilization. Polymers 2021, 13, 2135. https://doi.org/10.3390/Polym13132135

Fowler, D. Polymers in concrete: A vision for the 21st century. Cem. Concr. Compos. 1999, 21, 449–452.

Polycare, 2021. URL: https://polycare.de/en/polyblocks

Supplemental Cementitious Materials

Amran, M. Fediuk, R., Murali, G., Vatin, N., Karelina, M., Ozbakkaloglu, T., Krishna, R.S., Kumar, Kumar, S., Mishra, J. (2021). Rice Husk Ash Based Concrete Composites: A Critical Review of Their Properties and Applications. Crystals 2021, 11(2), 168; https://doi.org/10.3390/cryst11020168.

Easton, T. (2014). Watershed Materials. URL: https://watershedmaterials.com/blog/2014/4/24/reducing-cement-content-in-masonry-with-rice-husk-ash-a-promising-supplementary-cementitious-material (last accessed 06/09/2021)

Gautam, A., Batra, R., Singh, N. (2019). A study on use of rice husk ash in concrete. Engineering Heritage Journal (GWK)3(1) (2019) 01-04. Doi: http://doi.org/10.26480/gwk.01.2019.01.04

Hammond, G.P., Jones, C.I., (2008). Embodied energy and carbon in construction materials, Proc. Inst. Civ. Eng.: Energy 161 (2) (2008) 87–98

Henry, C.s., Lynam, J.G. (2020). Embodied energy of rice husk ash for sustainable cement production. In. Case Studies in Chemical and Environmental Engineering (2) 2020, https://doi.org/10.1016/j.cscee.2020.100004

https://www.edgebuildings.com/wp-content/uploads/2017/12/IFC-India-Construction-Materials-Database-Methodology-Report.pdf (last accessed 06/09/2021)

International Finance Corporation (IFC) (2017). Report India Construction Materials. Database of Embodied Energy and Global Warming Potential. URL:

Jing He, J. Kawasaki, S. Achal, S. (2020). The Utilization of Agricultural Waste as Agro-Cement in Concrete: A Review. In: Sustainability 2020, 12, 6971; doi:10.3390/su12176971

Malagavelli, V., Rao, P.N. (2010). High performance concrete with GGBS and Robo sand. International Journal of Engineering Science and Technology Vol. 2(10), 2010, 5107-5113. ISSN: 0975-5462.

Msinjili, N.S., Schmidt, W. (2014). Rice husk ash as a constituent material for low-cost housing in Africa. Cement & Concrete Technology.

R. N. Krishna, (2012). "An Ideal Admixture for Concrete in Aggressive Environments." In: 37th Conference on Our World in Concrete & Structures.

Vargas, J., Halog, A. (2014). Effective Carbon Emission Reductions from Using Upgraded Fly Ash in the Cement Industry. Journal of Cleaner Production. DOI: 10.1016/j.jclepro.2015.04.136

Recycled Materials

Breathe Architects (n.d.) Arkardia Apartments. https://www.breathe.com.au/project/arkadia

Deng, X., Liu, G., & Hao, J. (2008). A study of construction and demolition waste management in Hong Kong. International Conference on Wireless Communications, Networking and Mobile Computing, WiCOM 2008, pp 1-4.

DKO Architects (n.d.) Arkadia Apartments. https://dko.com.au/project/arkadia/

ECRA – European Cement Research Academy (2015). Closing the loop: What type of concrete re-use is the most sustainable option? A-2015/1860 Technical report. URL: https://www.theconcreteinitiative.eu/images/Newsroom/Publications/2016-01-16_ECRA_TechnicalReport_ConcreteReuse.pdf

Kuittinen, M. (2016). "Does the use of recycled concrete lower the carbon footprint in humanitarian construction?", International Journal of Disaster Resilience in the Built Environment, Vol. 7 No. 5, pp. 472-488. https://doi.org/10.1108/IJDRBE-04-2015-0016

Luis F. Jiménez, L. F., Domínguez, J.A., Vega-Azama, R.E. (2018). Carbon Footprint of Recycled Aggregate Concrete. Hindawi Advances in Civil Engineering Volume 2018, Article ID 7949741, 6 pages https://doi.org/10.1155/2018/7949741

Thormark, C. (2000). Environmental analysis of a building with reused building materials. International Journal of Low Energy & Sustainable Building, 1.

Xiao-shuang, S., Qing-yuan, W., Ci-chang, Q., & Xiao-ling, Z. (2010). Recycling Construction and Demolition Waste as Sustainable Environmental Management in Post-earthquake Reconstruction. 4th International Conference on Bioinformatics and Biomedical Engineering, iCBBE 2010.

3D Print

Adaloudis,, M. Roca, J.B. (2021). Sustainability tradeoffs in the adoption of 3D Concrete Printing in the construction industry. Journal of Cleaner Production 307 (2021) 127201.

Hossain, A., Zhumabekova, A., Suvash, P., and Kim, J.R. (2020). A Review of 3D Printing in Construction and its Impact on the Labor Market. Sustainability 2020, 12, 8492; doi:10.3390/su12208492

Rael, R., Fratello, V.S., 2018. Printing Architecture: Innovative Recipes for 3D Printing. Chronicle Books.

World's Advances saving Projects (WASP) (2012). TECLA – Technology and Clay The first eco-sustainable house 3D printed from raw earth is now a reality. Press release, 2021.

Deutsche Gesellschaft für
Internationale Zusammenarbeit (GIZ) GmbH

Registered offices
Bonn and Eschborn

Friedrich-Ebert-Allee 32 + 36
53113 Bonn, Germany
T +49 228 44 60-0
F +49 228 44 60-17 66

Dag-Hammarskjöld-Weg 1 - 5
65760 Eschborn, Germany
T +49 61 96 79-0
F +49 61 96 79-11 15

E info@giz.de
I www.giz.de

On behalf of

Federal Ministry
for Economic Cooperation
and Development