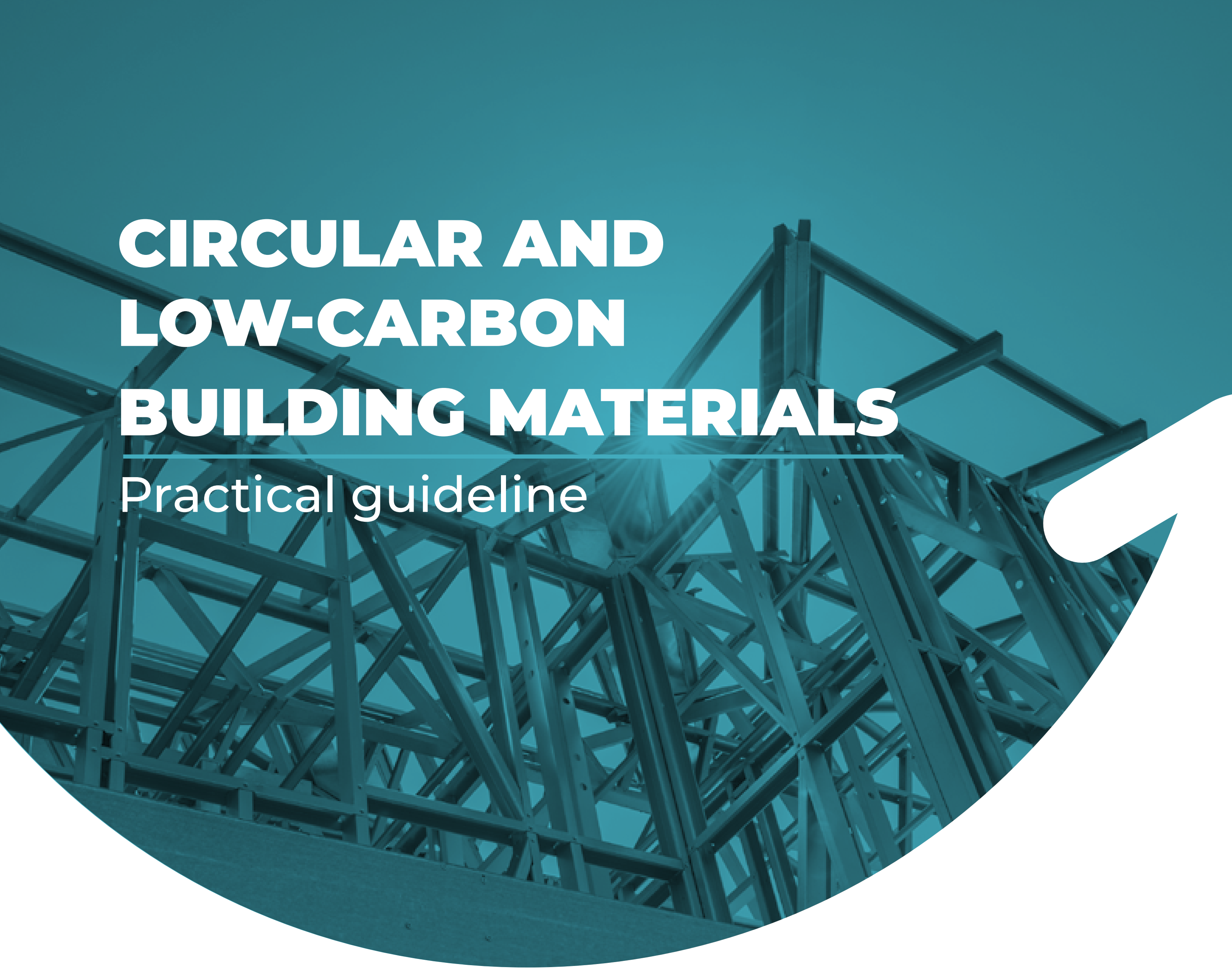

CIRCULAR AND LOW-CARBON BUILDING MATERIALS

Practical guideline

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1. Introduction to circular and low carbon building materials

The promotion of environmentally sustainable products has generated interest in bio-based materials, materials with recycled content, and the beneficial utilization of waste (secondary) materials. From an environmental standpoint, environmentally sustainable materials are those with minimal embodied energy. The embodied energy in building materials refers to the total energy consumed throughout the lifecycle of a material. This includes the energy required for the extraction of raw materials, manufacturing, transportation, construction, maintenance, and disposal or recycling at the end of its life. To progress along the path toward environmentally sustainable materials, including low-carbon building materials, the industry must prioritize the optimization of existing environmentally sustainable technologies. Additionally, there is a need to explore new technologies, optimize conventional methods, integrate fringe technologies into mainstream practices, expedite the adoption of hybrid technologies, investigate biotechnology applications, and delve into nanotechnology applications (van Wyk et al., 2012).

Nevertheless, a substantial reduction or radical departure from conventional bulk materials is unlikely in the short to medium term. Emerging trends may manifest in insulation materials, a shift away from ceramic products, reduced use of zinc and copper in piping in favor of PVC and other plastics, an inclination towards biocomposite materials, and increased utilization of recycled materials, notably in concrete through aggregate substitution, as well as in steel and aluminum (Van Wyk et al., 2012).

It is imperative for the construction industry at large, and manufacturers of construction materials in particular, to identify environmental bottlenecks associated with current and future material production and consumption. Equally important is the recognition of technological opportunities to address these environmental challenges. The focus should be on the environmental impacts (including, but not solely global warming potential) of materials arising from production processes (extraction, energy, and water use) and end-of-life treatment (waste handling and recycling). In certain cases, the in-use phase may dominate the overall environmental impacts of product life cycles due to continuous energy and/or material consumption during use, as exemplified in buildings (operation, maintenance, repair) (van Wyk et al., 2012).

Traditionally, the primary approach to addressing this issue has revolved around the application of energy-efficient strategies, which have proven effective, especially for constructions lacking energy regulations and constructed with subpar quality. Presently, the most ambitious retrofits aim to attain the Nearly Zero Energy Building standard, which has become the benchmark for new constructions in Europe. However, as operational energy demand decreases and renewable energy systems are integrated into buildings to balance the residual energy requirement, the environmental burdens of buildings are significantly shifted from operation to the construction stage; e.g. to building materials considering their embodied energy and embodied GHG emissions (Asdrubali and Grazieschi, 2020).

The integration of circular economy principles has the potential to make a significant dent in the embodied emissions associated with building materials, as evidenced by a multitude of EU-funded projects that aspire to achieve a remarkable 50% reduction. This matter holds particular gravity due to the construction sector's substantial contribution, responsible for over 40% of primary energy consumption in Europe and a sizable 36% of the European carbon footprint (Eurostat, 2020). An example of carbon (e.g. GHG emissions) embodied in various building materials is shown in Table 1.

To promote the reduction of a building's overall carbon footprint, the European Union has issued various studies, directives, and frameworks including the Energy Performance of Buildings Directive (EPBD), the Energy Efficiency Directive (EED), the Waste Management Directive, the Green Product Procurement Directive (GPP), Ecodesign Directive, the Level(s) framework, the Taxonomy Directive etc.

In the context of circular and low-carbon building materials, it's important to highlight the role of circular public procurement. This serves as a policy instrument to achieve environmental quality objectives. The goal of this instrument is to use demand as a lever, facilitating and accelerating the transition from a linear to a circular economy. Specifically within the construction sector, demand creates a market for recyclates and innovative circular and low-carbon products. Circular public procurement, therefore, plays a crucial role in fostering an environmentally sustainable construction sector. ***More details about circular public procurement can be found in the related document "Circular Procurement Guideline"***.

This guideline focuses on circularity at the material level, whereas circularity at the level of the entire building or construction is addressed in the associated guideline titled *"Circular Building Strategies"*. The latter guideline offers insights into principles of circular building design, including design for disassembly, reversibility, adaptability, reconfiguration, and spatial transformability. Additionally, it provides an overview of potential tools for circularity feedback.

As low carbon building materials often include secondary materials, the related guideline ***("Safe use of secondary building materials. Information package for producers")*** is recommended to read for further information. Among others, it provides requirements concerning assessing technical characteristics and environmental and health impacts of using secondary materials, construction products containing them, and recycled and re-marketed materials.

Table 1: Embodied carbon of various building materials (Source: Calkins, 2009).

Building material	Embodied carbon (kg of CO_2/ton)
Limestone	12
Stone/gravel chipping	16
Rammed earth	24
Soil cement	140
Concrete, unreinforced (strength 20 MPa)	134
Concrete, steel reinforced	222
Soft-wood lumber	132
Portland cement, containing 64–73% of slag	279
Portland cement, containing 25–35% of fly ashes	858
Local granite	317
Engineering brick	850
Tile	430
Steel, bar and rod	1720
Polypropylene, injection molding	3900

1.1. Purpose of the Guideline

The presented guideline aims to summarize existing knowledge on low carbon building materials and the circular economy strategies that can alleviate the environmental impacts associated with building systems and components. The guideline is primarily intended for policymakers, manufacturers of building products, waste managers, public investors, and other parties involved in the construction sector. Considering the information presented in this guideline, interested parties can contribute to making the construction sector more environmentally sustainable. In doing so, they play a crucial role in achieving the climate goals set in the Paris Agreement and facilitating the transition to a circular economy.

2. Circular materials

The circular economy strategy for building materials is based on multipronged approach. The main focus is given to the development of new materials and advanced construction methods designed to improve building performance and durability while minimizing waste. Carbon-negative building materials provide an avenue for long-term carbon sequestration as well as improved performance and durability. Advanced construction methods incorporate these new materials while reducing overall material consumption and increasing reuse potential.

Circular materials are designed to enable complete recycling of materials and novel synthesis strategies free from toxic precursors or by-products to regenerate raw materials. Circular materials shall be processed first at the local level for local needs (Dumée, 2022). Circular material use in construction is based on principles of maximizing the use of virgin materials and bio-based materials, maximizing the potential for high-value reuse, and the amount of recycled materials used. In 2021, the estimated circular material rate in the European Union was 11.7% (Andabaka, 2023), meaning that there is still a need for significant improvements.

An aspiration is to have closed-loop material flows that underpin a Circular Economy (CE) by keeping the matter making up materials in use as products longer and maximizing matter's regeneration into high-value products at the product's end of life. In this way, waste is minimized, and materials are reused, recycled, or repurposed at the end of their useful life.

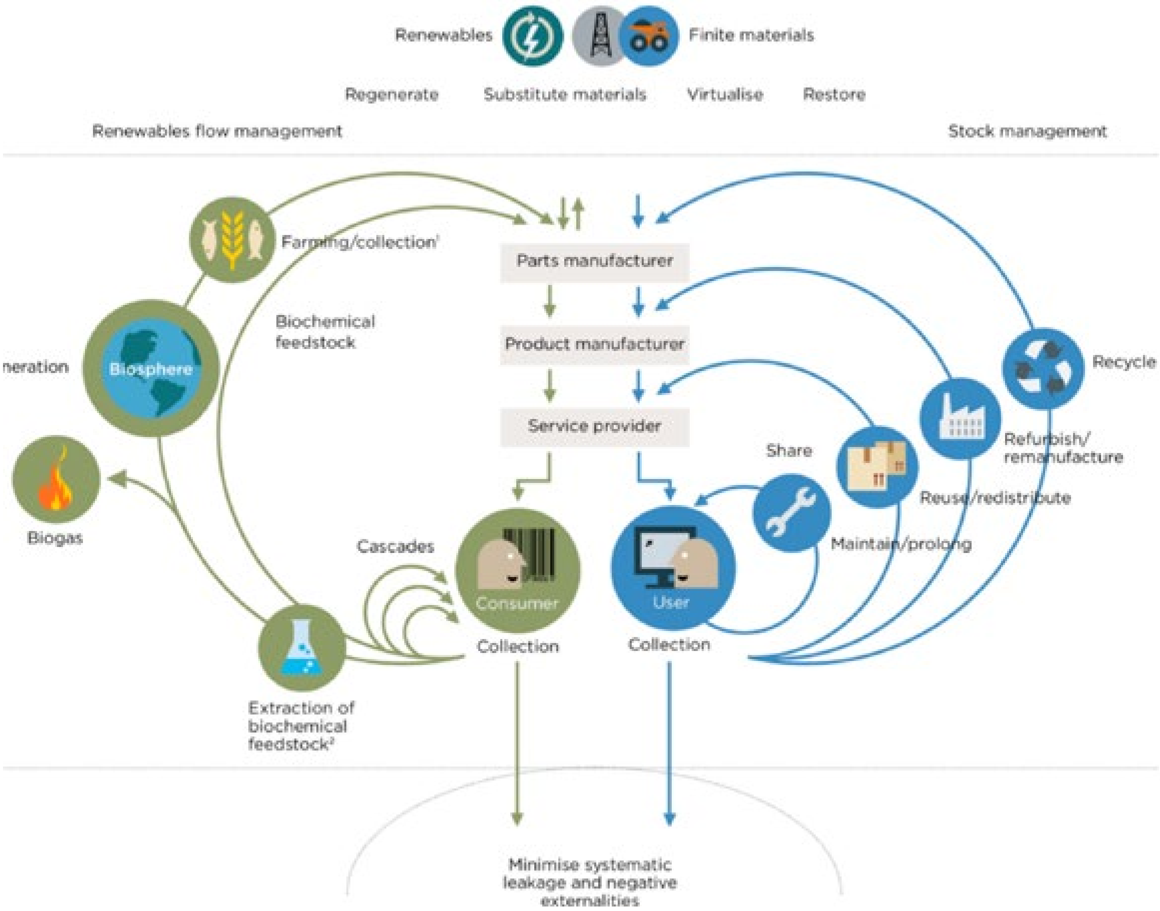
Circular Economy is an economic model that aims at optimizing resource usage within planetary boundaries, maximizing the value of assets in the economy, and minimizing waste by closing economic loops (Figure 1). Circular economy perceives the totality of economic value in a long-term perspective, i.e. it takes into account the costs of all externalities (environmental, social, etc.), and the discounted value of assets in their entire lifecycle. The circular economy can be defined as an industrial system intentionally designed for restoration and regeneration. It aims to replace the concept of disposal "end-of-life" with regenerative growth, prioritize renewable energy, eliminate toxic chemicals that hinder reuse, and strive for waste elimination through superior material, product, system, and business model design (Ellen MacArthur Foundation, 2013).

The circular economy is an approach to enhance sustainability. The circular economy entails gradually decoupling economic activity from the consumption of finite resources, and designing waste out of the system (Figure 1). It is based on three principles:

- Design out waste and pollution
- Keep products and materials in use
- Regenerate natural systems

The objectives of Circular Economy approach are thus to enhance the lifetime of products, facilitate the repurposing of items, and divert waste materials from landfills back to production lines. In the long term, such approaches will lead to further rational design of products, which may be easily dismantled into core parts for repurposing or recycling (Dumée, 2022).

Figure 1: The butterfly diagram of circular economy.



Source: Ellen MacArthur Foundation (2013)

Manufacturers need to design products according to sustainability requirements. This can be achieved through developing longer-lasting solutions (design for durability) and ensuring that product conceptualization considers not only the cost of manufacturing but also the repurposing, dismantling, and recycling of commodities (Dumée, 2022).

Considering building level, construction works must be designed, built and demolished in such a way that the use of natural resources is sustainable and ensures in particular: reuse or recycling of buildings and non-building structures, as well as their materials and parts after demolition, thus ensuring the durability of building structures; use of environmentally sustainable raw and secondary materials in building structures.

Circular design enables the creation of a sustainable built environment by making buildings more adaptable and facilitates the high-value reuse of a structures products and materials at the end of their life. Reversible building design is a design of buildings that can be easily deconstructed, or where parts can be removed and added easily without damaging the building or the products, components, or materials, thus focusing on their future use. Different layers like windows, floors, inner walls, and ventilation can be accessed without damaging other parts of the building enabling resource-efficient repair, replacement, reuse, and recovery of products, building materials, and components (Andabaka, 2023).

The principles of the circular economy, as delineated in the 2020 EU Circular Economy Action Plan and a fundamental component of the 2019 European Green Deal, draw inspiration from the waste hierarchy set forth in the EU Waste Framework Directive (2008/98/EC). This hierarchy categorizes approaches to managing materials at the end of their life cycle, with a central focus on preserving their economic value in the market, wherever feasible and environmentally optimal. Waste prevention takes precedence, followed by re-use, recycling, recovery, and disposal (e.g., landfill), which is the least favored option. Directly reusing building components stands out as the most ecologically appealing solution, though its practicality may be limited in the era of mass production (Stahel and MacArthur, 2019).

Conversely, the existing reutilization of mineral waste, a predominant constituent of construction and demolition debris, typically entails backfilling operations that do not significantly contribute to maintaining the economic value of these materials in the market. Concerns raised in the literature pertain to the use of materials with high recycled content and are linked to marginal cost increases for achieving equivalent mechanical performance in concretes, a reduction in workability, and the proximity of construction and demolition waste sources. ***More information about recycled materials can be found in the guideline „Safe use of secondary building materials. Information package for producers„***.

Different approaches how lowering the environmental emissions of the materials with the principles of Circular Economy (CE) are as follows:

- Reduce the impact of the materials by incorporating CE principles at the end of their lifetime (reuse, repair, refurbish, remanufacture, repurpose, recycle, and recover).
- The use of secondary materials (reused or recycled) for construction.
- Designing for durability.

2.1. Different types of recycling

These are the two main approaches when it comes to recycling. Roughly speaking, **closed-loop** recycling happens when the waste is used to manufacture similar products of the (group of) manufacturing company(ies) so that the recycling process can be repeated after each cycle.

In contrast, **open-loop recycling** occurs when the waste enters the waste trading business, and the waste is used by unknown parties.

Open-loop and closed-loop recycling should not be confused with 'upcycling' and 'downcycling'. Upcycling is bringing the raw material back to its original quality (grade), or even higher. Downcycling applies waste in its present form. Open loop downcycling is often done in a cascade of products, e.g. product A is concrete with natural gravel, product B is concrete with an aggregate of crushed concrete (e.g. recycled aggregate). Product C is crushed concrete (recycled aggregate) under a road.

3. Low carbon materials

Globally speaking, the building sector is responsible for 36% of all greenhouse gas emissions, around 40% of all material consumption, and 40% of all waste (Wouterszoon Jansen et al., 2022). Construction and operation of buildings have a key role in reaching targets from the Paris Agreement, which is to limit the increase of global temperatures below 2°C and to reach net greenhouse gas emissions neutrality in the second half of the twenty-first century (e.g. till 2050). In addition to this, the European Commission introduced a Green Deal with several proposals for reducing net greenhouse gas emissions by at least 55% by 2030, compared to the 1990 level and to make the European Union climate neutral in 2050.

The operational energy consumption in low-energy buildings has been significantly reduced in the last decades. A consequence of this is that the embodied GHG emissions of the building materials used in construction can account for around half of the life-cycle carbon footprint of the building. This problem can be tackled by producing low-carbon construction materials and implementing the circular economy principles, which can lead to a significant reduction of the embodied emissions of building materials (Grazieschi, 2022).

For buildings to become carbon-positive, a measurable and significant volume of CO_2 must be removed from the atmosphere and contained as carbon in building materials, and this quantity of stored carbon must be greater than the emissions associated with the harvesting, manufacturing, and transportation of all the materials used in the building. To achieve this, technologies such as bioenergy with carbon capture and storage have been introduced in the building sector. Carbon from the atmosphere can be stored in building materials in two ways: (i) permanent sequestration in mineral materials and (ii) temporary storage in biogenic materials (Magwood, 2019).

The main strategies (Andabaka, 2023) to reduce the embodied carbon in buildings or the carbon content of building materials and through this, the embodied carbon of buildings are listed as follows:

1. Design for **durability** (e.g. longevity of materials - longer use of the materials)
2. Design for **adaptability**
3. Design for **disassembly** and separation at source.
4. Application of **circular economy (CE) principles** (reduction of waste generation, direct re-use of materials from waste or demolition, use of recycled materials, refurbish, remanufacture, repurpose, recover etc.)
5. Use of materials with a **low carbon footprint** (such as bio-based materials) to replace high embodied carbon ones (such as concrete) without concessions on durability
6. Increase the **environmental performance** of the production chains (energy efficiency, renewable energy integration, technological development, industrial symbiosis etc.)
7. Use of **local products**

Design for durability/longevity, design for adaptability, and design for deconstruction/disassembly are strategies that are implemented at the building level. However, these strategies are reflected at a material level as well, considering less demand for new production of building materials and less waste generated over time. Materials that support these strategies contribute to a reduction in the carbon footprint of buildings.

Design for longevity seeks to achieve timeless architecture while using durable products and materials that can be adapted and reused in the future. Longevity allows the resources used in building construction to last a long time (e.g. slowing down the loop).

Design for adaptability enables the building to redefine its purpose without major interventions and to use considerably less material compared to major renovation, it reduces the need to demolish and avoids a considerable amount of construction and demolition waste. Adaptable buildings can undergo spatial change and functional changes during their lifespan, thus allowing for multiple life cycles. Increased adaptability is provided by using modular concepts, easy-to-change façades allowing for changes in building appearance and functionality, and plug-and-play technical installations.

Design for deconstruction/disassembly facilitates the deconstruction of a building at the end of its useful life, in such a way that components and parts that outlast their service life as part of a system (building) can be recycled, reused, or recovered for further economic use. Building deconstruction can be facilitated by reducing building complexity through favoring the modularity and lightness of the components, prefabrication and the simplification of the connections between the structural and non-structural elements, and minimizing the number and types of components; choosing reusable and eco-compatible materials whilst minimizing the use of hazardous and composite materials; and providing the information on the building construction and deconstruction. Deconstruction also includes securing the current construction, the analysis of the building's contents, the decontamination and removal of any hazardous waste, the demolition activities, and the recycling operations to recover the value of the existing materials.

For further information about circular design strategies see the guideline „Circular building strategies".

The reusability and recyclability of building materials, along with their overall circularity and other CE principles, represent approaches aimed at minimizing the carbon footprint and other environmental impacts during the end-of-life stage of these materials. Using resources more efficiently important aspect to reduce greenhouse gas emissions (GHG). For instance, it has been estimated that in 2050 applying combined circular practices in construction (such as modular design, use of lighter materials, reduced use of steel, recycling of unreacted cement, and increased utilization of buildings through sharing activities) could reduce up to 80 megatons of GHG emissions in the EU per year (cityloops.eu, 2023).

3.1. Possible ways to produce low carbon products for construction

Several approaches and recommendations exist for the manufacturers of building materials to reduce the environmental footprint (especially the carbon footprint) of their materials. These approaches greatly rely on the principles of the circular economy

Possible ways to produce low carbon products for construction described by Orsini and Marrone (2019) are as follows:

- use of alternative materials,
- use of natural materials,
- introduce secondary raw materials,
- implement Carbon Capture and Storage (CCS) and Carbon Capture and Utilization (CCU) systems in the production process,
- increase the use of energy from renewable sources and
- increase product performance.

3.1.1. Use of alternative materials:

A typical example is concrete, where the environmental impact is strongly linked to the production of Portland cement. This process involves the emission of more than 1 ton of CO_2 per ton of cement produced. Various alternative materials can be used as a replacement for cement to produce concrete with a relatively lower carbon footprint.

- coal fly ash (by-product of the combustion of pulverized coal in thermoelectric plants),
- granulated slag (a by-product of the production process of cast iron, during which large amounts of liquid slag are formed, not so different from that of Portland cement),
- silica fume (a by-product of the electric furnace production industry of metallic silicon and iron-silicon alloys),
- red clay brick waste,
- etc.

Benefits:

- reduction of carbon footprint and other environmental impacts (which needs to be verified by LCA method),

Barriers to using alternative materials in the concrete production sector:

- risk of loss of performance,
- the rarity of some alternative materials,
- lack of knowledge in the production sector,
- differing aesthetic appearance.

3.1.2. Use of secondary materials

This approach is based on use of reused, recycled, and waste materials. Some examples are:

- Using materials from demolition (construction and demolition waste - CDW). Using CDW can help in reducing the carbon footprint of concrete based on secondary materials.
- Using End-of-Life construction wood as a raw material in cross laminated timber.
- The use of waste material, such as fly ash and furnace slag in concrete production can reduce GHG emissions.
- Recycled/waste materials, could also be applied to bricks, resulting in reduction GHG emissions.
- Road pavements constructed with different recycled materials (reclaimed asphalt pavement, steel slag etc.).

There are several challenges related to the use of secondary materials:

1. Availability and quality of secondary materials pose a challenge in finding suitable and consistent sources for recycling or reuse. Insufficient collection and separation systems can also limit the availability of high-quality secondary materials.
2. Adequate infrastructure for collecting, sorting, and processing secondary materials is crucial. Implementing efficient collection systems and investing in modern sorting facilities can be expensive and require coordination among various stakeholders.
3. The economic justification for using secondary materials depends on market demand, production costs, and prices. If the costs of collecting, sorting, and processing secondary materials exceed the value of the obtained products, promoting their use can be unproductive.

4. Effective regulations and policies play a significant role in promoting the use of secondary materials. Clear guidelines, standards, and enforcement mechanisms need to be established to ensure the quality, safety, and compatibility of secondary materials with existing production processes.
5. Encouraging consumers to adopt products made from secondary raw materials can be a challenge. Awareness, public education, and promoting the benefits of using secondary raw materials are essential for changing consumer behavior.
6. Incorporating larger quantities of secondary materials into production may require adjustments or upgrades to existing infrastructure and technologies. Issues of compatibility and technical limitations may arise when integrating secondary materials into manufacturing processes, necessitating investments in research and development.
7. Managing a complex supply chain involving multiple stakeholders, including collectors, processors, manufacturers, and retailers, can be challenging. Coordinating activities, ensuring transparency, and maintaining quality control throughout the entire supply chain are crucial for the successful integration of secondary materials.
8. Overcoming societal prejudices regarding the use of secondary materials is crucial. Some people may still associate recycled or reused materials with lower quality, which can hinder their acceptance in various industries and consumer markets.

Benefits:

- Using CDW in the production process leads to the preservation of landfill space and reduces the impacts of the construction of new residential buildings. Using CDW can help in reducing the carbon footprint of concrete based on secondary materials.

Additional barriers:

- missing EU standardization on the trade of secondary raw materials,
- legislation on the use of secondary raw material,
- increased cost for equal design strength,
- loss of workability,
- distance limit concerning the provision of the CDW,
- lack of knowledge in the production sector,
- the differing aesthetic appearance,
- lack of social acceptance,
- lack of required processing infrastructure,
- not sufficient supply chain.

Using secondary materials can lead to a reduction of environmental impacts, including carbon footprint. However, the most important influential factors are the quality of both, the initial demolition material and the final construction product, defined by the product requirements.

Additional information about secondary materials and their application in building materials can be found in the document „Safe use of secondary building materials - Information package for producers”.

3.1.3. Use of natural (bio-based) materials:

Typically, bio-based materials that can replace high-embodied-carbon building materials, such as concrete and bricks, without compromising on durability is construction wood.

Another example of bio-based building materials is earth mixed with natural binders (lime, fly ash), or natural fibers (wood, hemp, sheep wool, materials from the agricultural sector).

Benefits:

- low level of processing and low-cost products,
- health safety of the product,
- local availability,
- the potential to activate local innovative chains capable of recovering aspects of the construction tradition and
- sequestration of biogenic carbon in natural materials. Some natural materials absorb a greater quantity of carbon during the whole life cycle than emitted quantity of carbon during the production of the product itself.

Barriers:

- need to compensate low performance by increasing the thickness of building products,
- lack of knowledge in the production sector and
- lack of skilled workers.

3.1.4. Use of local materials:

Greenhouse gas (GHG) emissions can be reduced by minimizing the transport distances of raw materials. The most preferable option is to use materials from demolitions directly on-site.

Barriers:

- the necessity to compensate for low performance by increasing the thickness of the components/building products,
- lack of knowledge in the production sector,
- distance limits for procurement ***(related to „Circular procurement guideline„)***,
- space required for the temporary storage of the materials from the demolition.

3.1.5. Performance increase

Performance increase is related with optimization, for example to:

- use smaller amount of raw materials,
- improving design in terms of GHG reduction,
- developing new materials based on nanotechnologies that could improve the performance of traditional materials (wood, concrete) and improving design in terms of GHG reduction.

Benefits:

- reduction of emissions,
- saving natural resources.

Barriers:

- lack of knowledge in the production sector,
- high costs of research and development.

3.1.6. Renewable energy integration

Energy is used in all life cycle stages of the building material (production, application, disposal/recycling). GHG emissions can be reduced by using energy from PV (solar), wind turbines, hydropower and other renewable energy sources) and also by using waste materials to produce energy (heat/electricity).

Benefits:

- reduction of GHG emissions

Barriers:

- high costs for the introduction of renewable sources

3.1.7. Other approaches

Ways to reduce GHG emissions are related also to:

- heat recovery from the production process and its reintroduction into the process itself,
- technological development or innovation of the production process,
- increase in production of process efficiency,
- energy efficiency,
- industrial symbiosis,
- biotechnological carbon capture,
- introduction of systems such as carbon capture and sequestration, carbon capture and utilization,
- etc.

In addition to these approaches for manufacturing low-carbon building products, Grazieschi (2022) provided an overview of some initiatives related to circularity and low carbon building materials in the construction sector. The strategies to reduce the embodied carbon of buildings are also ***(related to guideline „Circular building strategies")***:

- Design for durability,
- Application of circular economy principles (reduction of waste generation, direct re-use of materials from waste or demolition, use of recycled materials),
- Design for disassembly and separation at source.

Other aspects can also be emphasized here, such as a strategy encompassing five pillars to maximize the effectiveness of current technologies and advance the research and development of new environmentally responsible technologies (Van Wyk, et al., 2012). The five pillars, designed to complement each other, involve:

- Enhancing the efficiency of current technologies.
- Incorporating environmentally sustainable fringe technologies into mainstream practices.
- Expediting the integration of hybrid technologies into mainstream applications.
- Creating applications for biotechnology in construction.
- Developing applications for nanotechnology in construction.

4. Arbitrary list of circular and low carbon building materials

Some of the possible circular and low carbon building materials are presented in Table 2. These materials are considered more environmentally sustainable due to their circular properties, reuse of secondary materials, and lower carbon footprint compared to traditional construction materials. However, the list is just an example and not a complete and fixed list of the building materials. The decision on which building materials to use in certain construction projects is case study dependent and as such cannot be generalized.

Table 2: List of building materials, which are considered to be circular and have relatively low carbon footprint.

	Figure	Functionality	Further comment
		Engineered wood products (EWP)	
Wood fibre insulation boards (WFIB)		Application as insulation material (roof, wall, floor, ceiling, interior, façade, attic)	
Cross-laminated timber products (CLT)		Alternative to reinforced concrete systems (concrete floor slab) and steel structures	Adhesives may be problematic
Laminated veneer lumber (LVL)		Application in beams, headers, columns (considering building structures), door and window headers, stair stringers, purlins and girders in building frames	Adhesives may be problematic
Glue laminated timber (Glulam)		Application in construction elements, building frames, column, beam etc. Alternative to steel structures and concrete floor slab.	Adhesives may be problematic.
Construction timber		Application in: construction elements, building frames, column, beam etc. Alternative to steel structures and concrete floor slab.	
		Concrete with the use of secondary materials	
Concrete with the use of recycled aggregated (C&DW)		Application may be limited as it depends on the quality requirements. Application in building foundations, construction of road bases, sub-bases and pavements, structural concrete elements, construction of embankments and retaining walls, production of precast concrete products etc	Recycled concrete degrades the durability of components, shortening their life spans.
Concrete with the use of blast-furnace slag		Application in foundations, slabs, and driveways, mass concrete applications (dams and foundations), production of pre-cast concrete products (blocks and panels), high-performance concrete.	Leaching of compounds.

	Figure	Functionality	Further comment
Concrete with the use of coal combustion fly ashes		Application in pavement construction, residential construction (foundations, slabs, driveways), precast concrete products (blocks, panels, pipes), construction of bridge structures (beams, columns, decks), dams, foundations etc.	Leaching of compounds.
Bricks with the use of secondary materials and reclaimed bricks			
Brick with dredged mud		Application in low-rise constructions (residential buildings, small structures), traditional and vernacular architecture, boundary walls and fences, storage sheds, agricultural buildings, and other non-residential structures, artistic and decorative applications.	
Brick with fly ash (FAB)		Construction of walls, partitions, and other structural elements, construction of commercial and industrial structures (offices, warehouses), construction of bridges and culverts, paving applications (driveways, walkways, and other outdoor surfaces), use for interior and partition walls, use in renovation and retrofitting projects etc.	Concerns related to potential contamination caused by waste materials and the slow industrial and public acceptance rate could be the reasons for the limitation
Brick with steel slag		Application for walls, facades, and other structural elements, construction of commercial and industrial structures (offices, warehouses, manufacturing facilities), bridges and culverts, construction of retaining walls, paving applications (driveways, walkways, and other outdoor surfaces), garden walls and decorative elements, sound barrier walls along highways, use for interior and partition walls etc.	Concerns related to potential contamination caused by waste materials and the slow industrial and public acceptance rate could be the reasons for the limitation
Brick with calcium carbide sludge		Paving applications (walkways, landscaping elements), application in decorative features in architectural designs, applications in low-strength or non-load-bearing structures.	Concerns related to potential contamination caused by waste materials and the slow industrial and public acceptance rate could be the reasons for the limitation. Structural limitations.
Reclaimed bricks		Application for building facades, creating pathways and walkways in gardens, parks, and residential landscapes, construction of patios and courtyards, construction or renovation of fireplaces and chimneys, constructing retaining walls, interior flooring, application in various architectural features (arches, columns, decorative elements), garden edging etc.	Usually not suitable for load-bearing applications. For such applications, strength requirements should be met.

	Figure	Functionality	Further comment
Steel			
Steel		Various applications: reinforcing bars (rebar), structural beams, pipes, sheets, automotive parts, containers, manufacturing of household appliances (refrigerators, washing machines, and stoves), construction and maintenance of railroad tracks and bridges, production of furniture (steel-framed chairs, tables, and other metal furniture items), reinforcement in concrete construction etc.	Steel is not really low carbon material due to the high-energy processes of mining, hardening, enrichment and rolling. However, steel can be recycled over and over to make new steel. From this point of view, it is circular material.
Geopolymers			
Geopolymers		Used as binders for sustainable building materials (alternative to lime and ordinary Portland cement), manufacturing of precast concrete products (blocks, panels, and pipes), road construction for the production of durable and high--strength concrete for pavements and other structural elements, production of insulating materials, fire-resistant coatings for structures and materials, 3D printing of construction components, production of ceramics, architectural elements (decorative panels, sculptures, and building facades).	
Other building materials			
Glass		Windows and doors, household items, furniture, greenhouse panels, etc.	
Rammed earth (wall)		Applied in small-scale constructions (residential homes), fencing and boundary walls, restoration of historical buildings, barns, storage buildings, sound barriers along highways.	
Gypsum board		Application for interior partition walls, suspended or drop ceilings, fire-resistant wall assemblies, acoustic panels, reducing sound transmission, archways, niches, decorative elements, etc.	
Hempcrete		Wall and roof insulation, constructin of non-load-bearing interior walls, in some cases exterior non-load-bearing walls, renovation and restoration of historical buildings, construction of tiny homes, etc.	
Reclaimed asphalt pavement		Application in road construction (asphalt mixtures, base and subbase construction, road resurfacing, and rehabilitation).	Not applicable in buildings but in other construction projects
Excavated soil		Application in backfilling, landscape levering, gardens, rehabilitation of brownfield sites, construction or renovation of sports fields, embankment material in road construction projects, in some cases a substitute for construction aggregates in certain applications, cover material in landfill operations.	Application of excavated soil should adhere to local regulations and guidelines to ensure environmental compliance and prevent contamination.

4.1. Engineered wood products

Mass timber can be used as a sustainable alternative to steel and concrete in construction. Mass timber panels are used as structural building components such as load-bearing floors and walls (Ahn et al., 2022).

In addition to construction timber, cross laminated timber (CLT) is one of the most common engineered wood products used in construction. It is manufactured using softwoods and polyurethane adhesives. Glue lamination technology allows the manufacturing of timber-based structural members with arbitrarily large sizes. This has enabled engineered timber products such as glue-laminated timber (glulam) and cross laminated timber (CLT) to become competitors of steel and reinforced concrete in the construction market of medium-to-high-rise multi-storey buildings (D'Amico et al., 2021). Possible applications of various engineered wood products are indicated in Table 2.

Taking into account the literature data, it is observed that a nonresidential mid-storey timber building option, utilizing CLT and glulam elements, has a higher embodied energy compared to its reinforced concrete equivalent. This disparity is attributed to the substantial use of energy-intensive CLT elements in the timber building option. However, the heavy timber option would result in lower GWP than the reinforced concrete option, because renewable-sourced energy consumption was predominant during the manufacture of CLT elements, together with higher feedstock energy contained in the CLT panels (Robertson et al., 2012).

Wood waste from demolition is most commonly processed into chips and used for either energy production (e.g. production of heat and electricity through incineration) or particle board manufacturing. Even landfilling of waste wood is still practiced. However, concerning Circular Economy approaches, attention should be given to the recyclability and reusability of engineered wood products. The reusability of engineered wood products at their end-of-life depends on the possibility of their separation during the dismantling phase. It is important to consider this issue already during the design phase (Pastori et al., 2022).

Another factor that has a significant influence on the environmental sustainability of engineered wood products is the use of impregnating substances and adhesives during their production, which release volatile organic compounds (VOCs) and formaldehyde. Recent advancements have led to the development of adhesive-free engineered wood products for structural applications (Pastori et al., 2022).

Contamination from the applied building materials that might contain hazardous substances concerns residential and public buildings and industrial facilities materials can be found in the document „Safe use of secondary building materials - Information package for producers”.

4.2. Concrete

Concrete is the most widely used man-made material in existence and second only to water as the most consumed resource on the Earth. In most European countries concrete makes more than half (in weight) of the materials in buildings, in the Netherlands for example 77%. The reason for being the most used building material is that it offers flexibility in shape, durability, and high resistance to compression, fire, and water. Traditional concrete is a building material with a significant impact on global warming potential (which is directly related to carbon footprint), the reason for this is the use of cement which is the most commonly used binding material in concrete. The cement industry is responsible for around 8% of the world's CO_2 emissions. The production of cement is also very energy-intensive and requires a significant amount of water (Graaf and Schuitemaker, 2022). For instance, cement plants in Czech Republic emit 2.84 MT of CO_2, 65% of these emissions are related to the calcination process during clinker firing.

Among the possible alternatives for the reduction of the environmental (carbon) footprint of conventional concrete is a synergistic merging of the waste sector and the concrete sector. The most promising raw materials for the production of „green concretes" can be obtained from construction and demolition waste (C&D waste). C&D waste is one of the largest solid waste streams since more than 450 million tonnes of this waste are generated annually in the European Union (Ortiz et al., 2010), 40% – 67% of which consists of concrete. In the Czech Republic, the weight of C&D waste lies in the range of 20-23 million tons annually. The recycling of end-of-life concrete (obtained from demolition sites) into useful materials such as recycled aggregate is an important way in which the volume of C&D waste could be significantly reduced. Other promising raw materials for the production of „green concrete" are different types of industrial waste, either in the role of aggregate or as a binder. Taking into account the sustainable management of these materials, secondary materials from one industry could ideally serve as a resource for another industry. However, the prerequisite for their use as a substitute for natural materials is their environmental acceptability and their technical adequacy.

1. Czech examples (adapted from Pavlů et al., 2018):

Considering Czech regulation, the concrete may contain slag aggregate that meets the requirements of ČSN EN 12620+A1.The use of slag aggregate depends on the type, origin, composition, properties and age of the slag. Concretes with slag aggregate are evaluated according to ČSN EN 206 + A1 - declaration of properties).

Concrete and precast concrete from fly ash filers. Fly ash filer can be used in concrete according to ČSN EN 450-1 (Declaration of Conformity) as a Type II admixture for the production of concrete, including site-manufactured concrete or precast concrete structural components that comply with ČSN EN 206-1 (now ČSN EN 2016+A1).

CSN EN 206+A2 [7] sets limits for the recycled aggregate content for concrete of the environmental impact level, depending on the source of the recycled aggregate. The standard allows a maximum of 50% by volume of recycled aggregates as a substitute for coarse natural aggregates for concrete.

All alternatives have to be evaluated concerning their environmental benefits and trade-offs, so this is why the use of the Life Cycle Assessment (LCA) method is widely applied nowadays. Several authors have studied the environmental impact of recycled aggregates versus that of natural aggregates, as well as the impact of concretes based on recycled/alternative materials versus that of conventional concretes, taking into account the results of LCA analysis. For instance, Blengini and Garbarino (2010) studied how recycled aggregates can complement natural aggregates in a sustainable supply stream for the construction industry. They showed that the C&D waste recycling chain can be eco-efficient since the avoided impacts are higher than the induced impacts.

In another study, Knoeri et al. (2013) analyzed the life cycle impacts of 12 alternative concrete mixtures and compared them with those of corresponding conventional concretes. The investigated concrete mixtures differed in their percentages of recycled aggregates, their cement type, and their cement content. It was found that concretes based on recycled/alternative materials can reduce environmental impacts to about 70% of those caused by conventional concretes. This was mainly attributed to the benefits obtained from the recovered scrap iron (from the steel reinforcement), as well as to the avoidance of the need to transport C&D waste to a landfill site, and to the avoided impacts of such disposal.

Replacing solely natural aggregates with recycled aggregates in the concrete production process does not yield a notable reduction in terms of carbon footprint. This was confirmed by Faleschini et al. (2014), who compared the production of concrete containing EAF C slag aggregate with the production of corresponding conventional concrete. EAF C slag was used to replace coarse-grained natural aggregate in various concrete mixes. The LCA results showed that the emissions related to the production of artificial aggregate from EAF C slag are significantly lower than those related to the extraction of natural aggregate. However, the cement content was slightly higher in the alternative scenario. Since cement is the main factor which is responsible for the emissions caused by concrete production, the analyzed alternative and conventional concretes showed quite comparable impacts. However, the results are sensitive to the type of transport used and to the delivery distances of the natural and recycled aggregates (Marinković et al., 2010).

A lot of studies deal with the evaluation of the carbon footprint of typical concrete mixes (for instance see Flower and Sanjanyan, 2007, Marceau et al., 2007; Zhang et al., 2014). Some cementitious components such as fly ash and ground granulated blast furnace slag (both are industrial by-products) show the potential to reduce emissions in the concrete production industry (for more details see studies of Flower and Sanjanyan, 2007 and O'Brien et al., 2009). The fly ash was found to be capable of reducing concrete greenhouse gas emissions by around 15 % and the blast furnace slag by around 22% in typical concrete mixes.

Considering the demolition of the concrete structure, the waste concrete can be recycled as a construction material (e.g. typically crushed to produce recycled aggregates) if it adheres to a quality class under the Construction Material Recycling Regulation. Recoverable materials include, for instance: concrete and reinforced concrete debris, precast concrete elements (e.g. columns, ceiling elements), and concrete foundations. Possible uses are fill material, backfill material, road construction sub-layers, substructures for building floors in construction, concrete aggregates, drainage layers etc (see Table 2). Landfilling is still practiced (around 11% of the waste concrete is landfilled in EU countries), especially when the concrete fraction is contaminated by other materials. However, concrete debris is considered non-recoverable when it cannot comply with a quality class demanded for its application. This is particularly applicable to the following materials: concrete debris from industrial areas, and concrete debris contaminated with pollutants (e.g., with tar coatings).

In the case of selective demolition of concrete structures, the waste concrete has fewer impurities and can be used in the production of recycled aggregate for concrete. Design for disassembly, such as modular construction and prefabrication enable reuse of concrete components. Precast column beams can be reused. The right type of joint can make it possible to reuse concrete floor systems and precast concrete facades (Tonini et al., 2023).

4.3. Brick

Bricks are one of the most employed building materials and also the oldest as they have been in use for more than seven thousand years. Traditional clay bricks, throughout their life-cycle, require non-renewable raw materials, high temperatures to be produced, and thus large quantities of energy emitting greenhouse gases potentially responsible for global warming (Ramos Huarachia et al., 2020).

To improve the environmental sustainability of bricks, alternative bricks are produced by adding industrial waste materials (see Table 2). Considering the life-cycle of alternative bricks, the differences compared to traditional bricks refer to (i) the extraction of raw material, (ii) the use of waste materials that replace clay completely or partially and (iii) the production stage - firing is often eliminated and replaced by stabilization processes.

To optimize the beneficial use of waste and secondary materials, fly ash, dredged mud, steel slag, calcium carbide sludge can be used in brick production (Table 2). For example, fly ash-sand lime bricks offer several advantages, including availability in various load-bearing grades, savings in mortar plastering, and the creation of aesthetically appealing brickwork. They impose no additional load on the structure's design, exhibit enhanced earthquake resistance through panel action with high-strength bricks, provide satisfactory sound insulation, offer maximum light reflection without glare, and demonstrate excellent fire resistance and durability (Ferrer Polancos, 2009).

Considering the end-of-life of bricks, the following recycling pathways can be recommended: (i) recycling to material for road construction and backfilling, (ii) recycling for replacement of cement in plasters, (iii) recycling to material (aggregate) for concrete production and (iv) alkaline activation. Moreover, end-of-life of bricks can be recycled to fine aggregate and used as clay sports ground surfaces. Brick recycling to material for road construction and backfilling seems to be the most common practice. In this kind of application, bricks are crushed together with other inert materials and used in the production of recycled aggregates (Fort and Černy, 2020).

Considering the design for deconstruction, the main strategy is the construction of mortar-free structures in which the bricks are connected by way of steel plates and wall ties. Prefabrication of modular units further increases the reuse potential of bricks (Tonini et al., 2023).

4.4. Steel

Steel is material widely used in construction due to its durability, flexibility, stress resistance, and its high density which allows the realization of relatively lightweight structures. It is used in almost all structural elements. Around 50% of the world's steel demand is related to the construction of infrastructure and buildings. Steel production is along with cement a major contributor to greenhouse gas emissions potentially affecting global warming. Considering the information of the World Steel Association from the year 2023, the production of one ton of steel yields 1.9 tons of carbon dioxide, which corresponds to about 8% of global CO_2 emissions. However, steel is a 100% recyclable material and keeps almost all of its original properties when reused. Steel can be recycled over and over to make new steel. The problem related to the recycling of steel refers to relatively high energy consumption. Nevertheless, recycled steel used in new buildings can be considered low-carbon material (Graaf and Schuitemaker, 2022).

Considering the demolition of the building or other structures, steel is typically collected for recycling. Therefore recycling of steel is the usual waste management practice. In the case of selective demolition, some steel components such as purlins, beams, and columns can be reused (Tonini et al., 2023). Reuse end-of-life treatment typically includes sandblasting of the steel component to remove paint, and repainting (adding new paint and zinc coating and as a protective layer).

4.5. Geopolymers

The „geopolymer" refers to an amorphous alkali metal silicoaluminate, characterized by a repeating sialate monomer unit (-Si-O-Al-O-). Regarded as the third generation cement, geopolymer serves as an alternative to lime and ordinary Portland cement. Geopolymer concrete can be produced by polymerizing the aluminosilicates such as fly ash, metakaolin, slag, rice husk ash, and high calcium wood ash through activation using alkaline solution. Hence the efficiency in producing geopolymer concrete is highly dependent on the activators as well as types of aluminosilicates resources. The production process of geopolymer concrete typically eliminates the need for OPC, which is the most used cement in a concrete mix. Geopolymers exhibit promising potential as binders for sustainable building materials, offering early compressive strength, low permeability, excellent chemical resistance, and remarkable fire resistance properties (see Singh et al., 2015). It is considered as a low carbon material as the production process requires less energy compared to cement. The use of geopolymer concrete as an alternative to conventional Portland cement concrete has been found to result in up to 80% reduction in embodied carbon depending on the precursor and activator used.

4.6. Reclaimed asphalt

Reclaimed asphalt is recycled low carbon material used in road construction. It consists of asphalt and aggregates reclaimed from existing asphalt pavements that have been removed, often during road maintenance or reconstruction.

Recycled asphalt pavement (RAP) serves as a valuable source of aggregates and bitumen. Integrating RAP into asphalt production not only extends the lifespan of current quarry resources but also diminishes the reliance on fossil fuels in bitumen manufacturing.

As for asphalt recycling, it can be broadly classified into „hot" and „cold," along with „in-place" and „at-plant" methods. In hot-in-place recycling, RAP is blended on-site with new materials from a hot-mix asphalt plant, followed by standard laying and rolling procedures. This approach is particularly efficient for promptly addressing surface course issues. In the case of „at-plant" recycling, RAP is transported to a central plant yard, where it is stockpiled and re-processed. Subsequently, RAP is treated as a raw material for hot-mix production. Significant savings in off-site recycling primarily stem from the materials within RAP, such as bitumen, aggregate, and mineral filler. Production of these materials is associated with GHG and other emissions. Savings of the virgin materials related with RAP recycling may result in the reduction of GHG and other emissions (Cheung, 2003).

Cold in-place recycling employs the „foamed bitumen" technique to rehabilitate deteriorated asphalt pavements. This method reclaims materials from the road using a recycling machine, generating a new pavement layer and revitalizing the existing pavement structure. Notably, this technique differs from other asphalt recycling methods as it eliminates the need to heat aggregates, thereby reducing energy consumption and consequently mitigation the emissions - including GHG (Thenoux et al., 2007).

Some literature examples showing the reduction of GHG due to RAP recycling are as follows. Giustozzi et al. (2012) studied the carbon footprint of the reconstruction of an airfield pavement. Two scenarios were compared: rehabilitation of the existing pavement by (1) using only virgin aggregates and bitumen, and (2) by using 85% of recycled materials. In the latter case, the greenhouse gas emissions were reduced by 35%. The energy consumption and greenhouse gas emissions corresponding to different types of road pavement rehabilitation and maintenance works have also been studied by Chappat and Bilal (2003), Chehovits and Galehouse (2010), Cross and Chesner (2011) etc.

To summarize, the use of RAP in road construction offers several environmental and economic benefits:

- Resource Conservation: Incorporating RAP into new asphalt mixtures conserves natural resources by reusing materials from old pavements.
- Energy Savings: The production of asphalt from RAP typically requires less energy compared to producing virgin asphalt from raw materials. This contributes to a reduction in overall carbon emissions.
- Cost Efficiency: Using RAP can be cost-effective since it reduces the need for new raw materials and minimizes waste disposal costs associated with old asphalt pavement.
- Improved Sustainability: By reusing existing materials, RAP promotes sustainability in road construction, aligning with environmentally conscious practices.

It's worth noting that the specific environmental impact and sustainability of road construction projects depend on various factors, including the percentage of RAP used, the overall mix design, and the transportation distances involved. Nonetheless, the incorporation of reclaimed asphalt is generally considered a positive step toward circular, more sustainable and low-carbon road construction practices.

4.7. Excavated soil

Excavated soil is material that is generated through the excavation or removal of soils and other natural materials, even after relocation.

Excavated soil must undergo a fundamental characterization by an authorized specialist or institution before it is deemed suitable for any purpose. Depending on the determined quality class under the Federal Waste Management Plan, the excavated soil material can be utilized for various applications, including as a reclamation layer, non-agricultural reclamation layer, and subgrade fill, both in and immediately above the groundwater, in areas with similar contamination situations, and as a recycling material for unbound and bound applications. For more details on the application, see Table 2.

4.8. Other low-carbon building materials

Other widely used relatively low-carbon building materials are **glass, gypsum board**, and various types of **insulation materials**.

Rammed earth wall and **hempcrete** are low-carbon building materials, which are not as widely used as traditional building materials. However, there has been a growing recognition of their benefits in terms of sustainability. As awareness of environmental concerns and the need for more ecological construction practices increases, these alternative materials are gaining popularity among architects, builders, and homeowners looking for "greener" building solutions.

Rammed earth involves compacting natural raw materials, such as earth, chalk, lime, or gravel, into solid walls. This construction technique is known for its thermal mass and insulation properties, contributing to energy efficiency in buildings.

Hempcrete is a composite material made from the inner woody fibers of the hemp plant mixed with lime and water. It is valued for its low environmental impact, carbon sequestration potential, and insulation capabilities.

Additional information on recycling and reuse practices of various building materials considering their end-of-life stage is available in the document „Safe use of secondary building materials - Information package for producers". Case studies for post-demolition building materials are presented in this document.

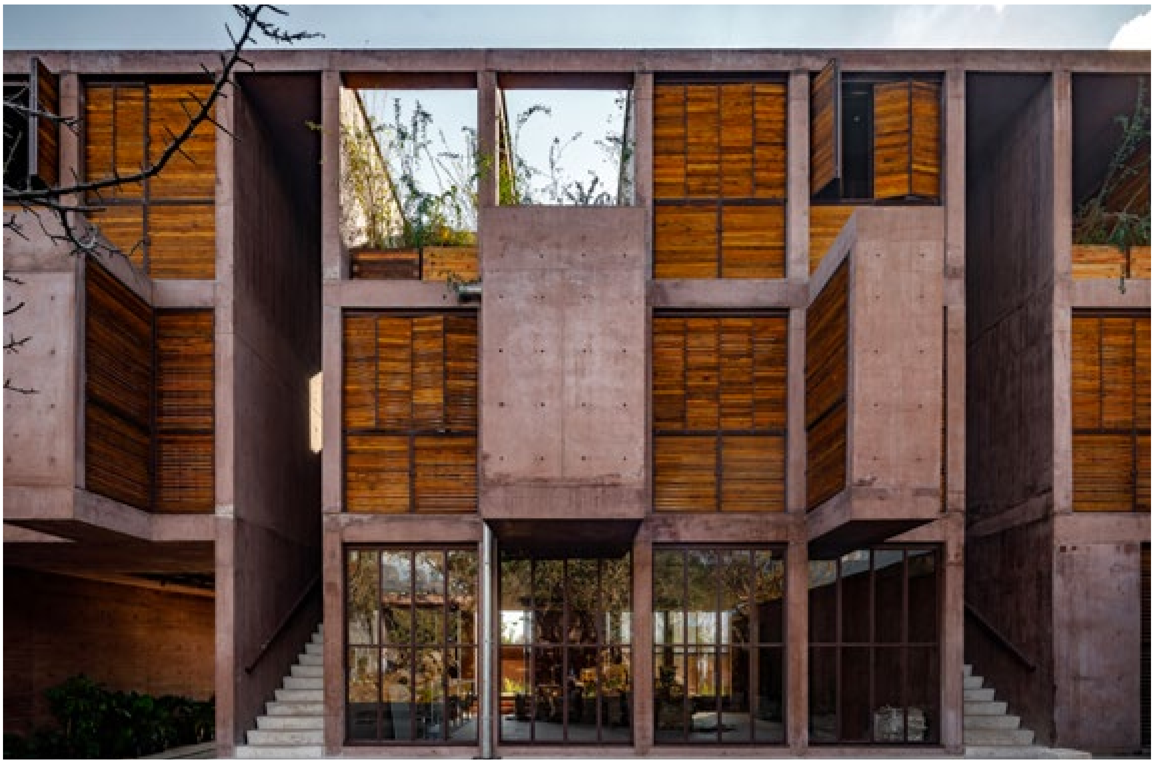
4.9. Case studies: constructions based on circular and low carbon building materials

Case study

Hotel Tepoztlán (Mexico, 2020):

- walls and pavement: local stone,
- visible concrete with natural pigments,
- wood formwork used in construction has been repurposed into furniture or flooring.

Figure 2: Hotel Tepoztlán [source: https://architizer.com/projects/tepoztlan-hotel/]



Case study

Cheops Observatory Residence / Studio Malka Architecture, Necropolis Giza (Egypt, 2020):

- local construction techniques,
- used recycled materials.

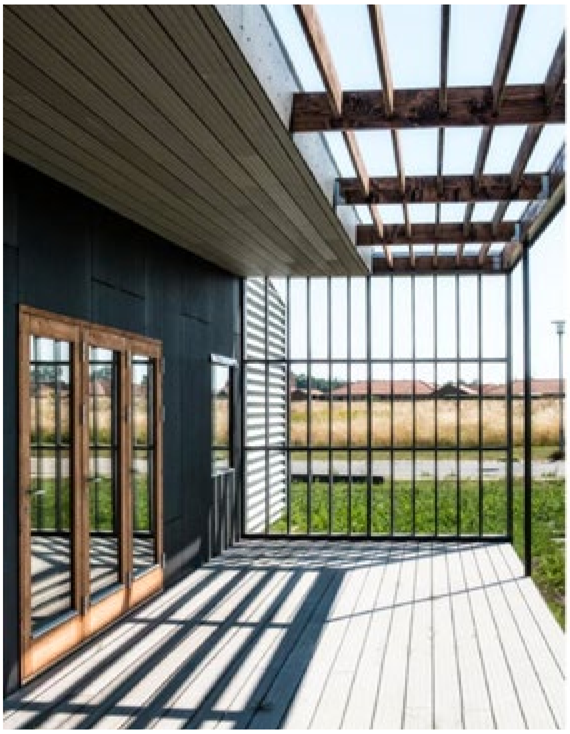
Figure 3: Cheops Observatory Residence [source: https://www.designboom.com/architecture/studio-malka-cheops-observatory-pyramid-giza-03-05-2020/]

Case study

Upcycle House, Lendager Arkitekter, Nyborg (Denmark, 2013):

- a house built with an emphasis on recycling and processing materials,
- used discarded materials,
- materials transformed into higher-value building materials

Figure 4: Upcycle House, Lendager Arkitekter, Nyborg [source: https://www.archdaily.com/458245/upcycle-house-lendager-arkitekter]



5. Life Cycle Assessment

By addressing the environmental performance of individual building materials/components, the overall environmental footprint of a building can be assessed. However, environmental impacts are associated with:

- Design and construction of the building (materials and elements used),
- Energy and water use during the building's operational phase,
- Potentials that manifest after the end of the building's use (suitability of materials and elements for reuse, etc.).

Life Cycle Assessment (LCA) is a method for evaluating the environmental performance (e.g. footprint) of a product or process. This method can therefore be used to evaluate global warming potential (e.g. carbon footprint) and set of other environmental impacts throughout the entire life cycle of a building, infrastructure, or simply of certain building material.

The LCA must be conducted following the principles and framework for LCA, which are defined in the international standard for LCA ISO 14040:2006 and ISO 14044:2006, ILCD handbook, and the European standard for Environmental Product Declarations (EPD) EN 15804:2012+A2:2019, which provide core product category rules (PCR) for Type III environmental declarations for any construction product and construction service. The standardization process has taken place by ISO 14025:2010. ***Additional information about circular standardized (normative) types of environmental labeling and declarations (including EPD) can be found in the guidelines "Safe use of secondary building materials - Information package for producers" and "Circular building design strategies"***.

There are four distinct phases in an LCA study:

1. The goal and scope definition phase, which sets out the context of the study by defining functional/declared unit, system boundaries, and any assumptions and limitations of the study.

2. The inventory analysis phase, which creates an inventory of input and output flows to and from the studied system, such as inputs of water, energy, and raw materials, and outputs to air, soil, and water.

3. The impact assessment phase, which aims at evaluating the significance and magnitude of potential environmental impacts based on the inventory analysis flow results.

4. The interpretation phase, where the findings from the results of the inventory analysis phase and/or the impact assessment phase are summarised and evaluated in relation to the defined goal and scope of the study.

The system boundaries of product LCA can be different, depending on the goal and scope of the study. The system boundaries can vary, depending on the type of data: cradle-to-gate or cradle-to-grave.

Cradle-to-gate: refers to the production stage, which includes the extraction of raw materials, their delivery to the factory (production site), and therein manufacturing of the final product.

Cradle-to-grave: In addition to the production stage, all other life cycle stages are included: installation phase, use phase, and end-of-life phase (decommissioning, removal, waste treatment, waste disposal).

For LCA used in eco-design, it may be relevant to include the recycling potentials of the products, thus extending the system boundary (a cradle-to-cradle approach).

Table 3: Stages included in the whole life cycle, considering a modular approach

SYSTEM BOUNDARIES																
Product stage			Construction process stage		Use stage							End-of-life stage				Benefits and loads beyond the system boundary
Raw material supply	Transport	Manufacturing	Transport	Installation process	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction demolition	Transport	Waste processing	Disposal	Reuse-Recovery-Recycling potential
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D

The system boundaries follow the modular structure in line with EN 15804 (Table 3). The description of the life cycle stages and modules is as follows:

Product stage:	**A1:** raw material extraction and processing, processing of secondary material input (e.g. recycling processes); **A2:** transport to the manufacturer; **A3:** manufacturing; including provision of all materials, products and energy, as well as waste processing up to the end-of-waste state, or disposal of final residues, during the production stage.
Construction process stage:	**A4:** transport to the building site; **A5:** installation in the building; including provision of all materials, products and energy, as well as waste processing up to the end-of-waste state or disposal of final residues during the construction process stage. These information modules also include all impacts and aspects related to any losses during this construction process stage (i.e. production, transport and waste processing and disposal of the lost materials).
Use stage:	**B1:** use or application of the installed product; **B2:** maintenance; **B3:** repair; **B4:** replacement; **B5:** refurbishment; **B6:** operational energy use (e.g. operation of heating system and other building re-lated installed services); **B7:** operational water use including provision of all materials, products and energy, as well as waste processing up to the end-of waste state or disposal of final residues during the construction process stage. These information modules also include all impacts and aspects related to any loss during this construction process (i.e. production, transport, and waste processing and disposal of the lost products and materials).
End-of-life stage:	**C1:** de-construction, demolition; **C2:** transport to waste processing; **C3:** waste processing for reuse, recovery and/or recycling; **C4:** disposal; including provision and all transport, provision of all materials, products and related energy and water use.
Benefits and loads beyond the system boundary:	**D:** reuse, recovery and/or recycling potentials, expressed as net impacts and benefits.

How to deal with the circularity in LCA? Reusing and often also recycling yield environmental benefits compared to production of new materials. Reuse can prevent the impacts associated with both extracting raw materials and manufacturing products. While recycling is mostly related with avoided extraction of virgin raw materials. Thus the environamental benefits attributed to reusing can be more significant than those attributed to recycling.

Different methodological approaches exist regarding how to address the benefits of reused building materials/components in LCA. However, no consensus has been reached on this matter within the LCA community. In the case of designing for disassembly, attention can be given to the fact that each structural or technical system in the building has its own service life. The approach is to focus on the unique service life for each component. In such a case, the entire building LCA could be composed by using a functional unit in which the lifecycle emissions of each component are divided by its historical and expected service life in years. An option for evaluating environmental impacts related to reuse could be applying the remaining service time as a compensating element in the building's LCA.

5.1. Examples of case studies for environmental assessment of building products

5.1.1. Concretes from secondary materials

In this case study, LCA is used as a tool to benchmark the production of traditional concrete versus the production of concrete with the use of secondary raw materials:

- Traditional concrete
- Concrete with the use of fly ash (as a partial replacement of the cement)
- Concrete with the use of foundry sand (as a partial replacement of the natural aggregate and cement)
- Concrete with the use of steel slag (as a partial replacement of the natural aggregate)
- Concrete with the use of recycled aggregate (as a partial replacement of the natural aggregate)

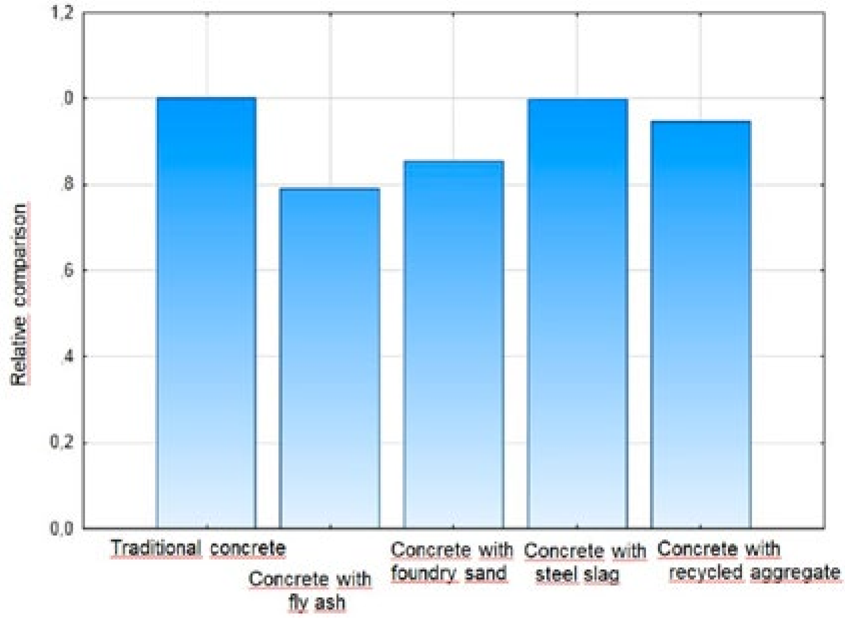
Considering the benchmarking, it is important that all concretes have similar compressive strengths and durability.

The results of LCA are as follows (see also Figure 5):

- Concrete with the use of fly ash:
reduction of carbon footprint by 21% compared to traditional concrete
- Concrete with the use of foundry sand:
reduction of carbon footprint by 18% compared to traditional concrete
- Concrete with the use of steel slag:
no reduction of carbon footprint compared to traditional concrete
- Concrete with the use of recycled aggregate:
reduction of carbon footprint by 7% compared to traditional concrete

More detailed information on this case study is available in the paper of Turk et al. (2015)

Figure 5: The global warming potential (carbon footprint) of 1 m³ of concrete.



5.1.2. Asphalt wearing course

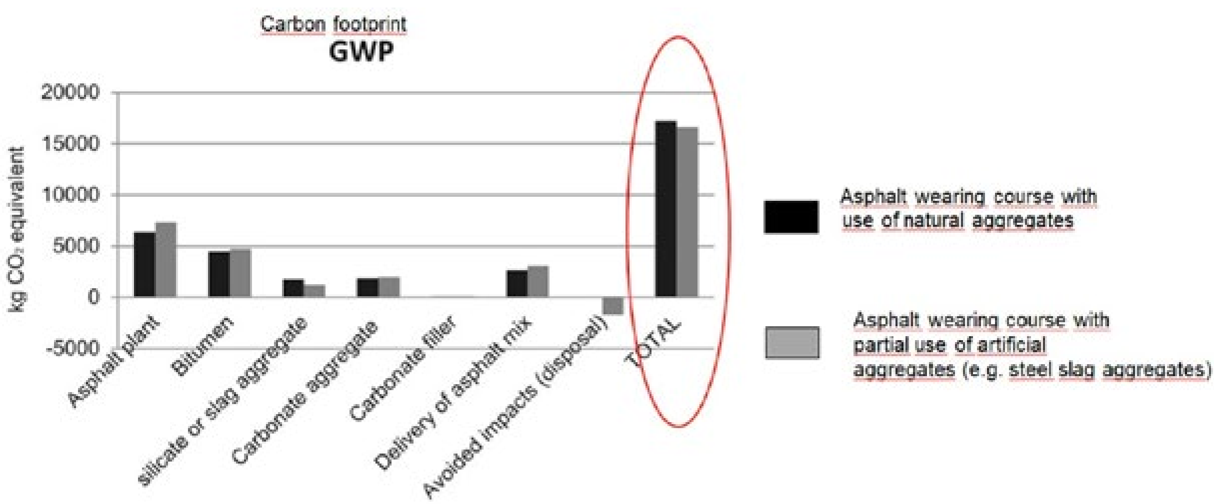
In this case study, LCA is used as a tool to benchmark two scenarios in the case of the construction of asphalt wearing course:

1. Production of asphalt wearing course with the use of conventional construction aggregates (carbonate and siliceous aggregates).
2. Production of asphalt wearing course with the use of EAF C slag aggregate instead of siliceous aggregates.

Results of LCA show that utilization of EAF C steel slag aggregate in asphalt wearing course results in the reduction of the carbon footprint of the asphalt wearing course by around 5% (Figure 6).

More detailed information on this case study is available in the paper of Mladenovič et al. (2014).

Figure 6: The global warming potential (carbon footprint) of 1 m³ of traditional and alternative asphalt mixes intended to be used for wearing course of the road.



5.1.3. Case study of steel

Varesa et al (2019) conducted a study, where they compared the environmental impacts on the life cycle of an industrial building. Considering the demolition of the building and construction of new industrial building, they compared the environmental impacts related to the reuse of steel components from demolished building in the new building versus new construction using new steel structures.

Considering the results of LCA, greenhouse gas emissions in the baseline scenario amount to 686 kg CO_2 equiv./m², while the emissions in the alternative scenario amount to 605 kg CO_2 equiv./m² (in case of reuse of steel components). The reduction of the global warming potential (or carbon footprint) over the lifetime of the building is therefore 12%, considering the reuse of steel components.

6. Summary and conclusions

The construction sector contributes around one-third of all global GHG emissions. As new constructions are characterized by reduced operational energy consumption, more and more attention should be given to the embodied components such as the embodied energy and Global Warming Potential (GWP) due to building materials. The construction sector should focus on addressing the environmental effects of materials arising from their production processes (including extraction, energy consumption, and water usage) as well as end-of-life management (involving waste handling, repurposing, reuse, recycling etc.).

Approaches and recommendations to reduce the environmental footprint (especially the carbon footprint) of building materials are gathered together in this guideline. These approaches greatly rely on the integration of bio-based materials, materials with recycled content, the beneficial utilization of waste (secondary) materials and on the principles of the circular economy; e.g. keeping the matter making up materials in use as products longer and maximizing matters regeneration into high-value products at the products end of life.

In this guideline, an arbitrary list of possible circular and low carbon building materials is presented. Each building material from the list is described, considering its application, circularity (end-of-life treatment), and environmental sustainability. However, the list is just an example and not a complete and fixed list of the building materials. It provides a tip for policymakers and other stakeholders, on how to make the building (construction) sector more environmentally sustainable and more aligned with circular economy principles. However, the decision on which building materials to use in certain construction projects is case study dependent and as such cannot be generalized.

The Life Cycle Assessment method is briefly introduced, as it stands out as the most promising tool for evaluating the carbon footprint and overall environmental impact of materials (building materials) and structures (buildings). Three practical examples can aid stakeholders in grasping the application of this method. These examples involve benchmarking the production of various building materials (traditional versus those with recycled content) and benchmarking linear end-of-life treatment techniques against circular end-of-life treatment techniques.

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