Earthen construction materials as enabler for circular construction

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Abstract. The construction sector in Germany is one of the largest contributors to climate change. The majority of waste generation, resource consumption as well as CO\textsubscript{2} emissions relate to the construction and operation of buildings [1][2][3]. In order to tackle such negative impacts, the construction industry has to undergo a major transformation. Circular construction is the most promising answer to close effectively material cycles and to reduce CO\textsubscript{2} emissions related to the manufacturing of construction materials. Stakeholders involved in construction have to review the entire life cycle of building products and buildings and develop new approaches that address such shortcomings to turn the linear way of construction into a circular one. Nowadays the strong focus on economic considerations, lacking knowledge as well as unresolved warranty issues amongst others impede this transformation process. To demonstrate the benefits of earthen materials with regards to circular construction, this study analyses the potential of two different internal partition wall systems, based on earthen as well as conventional building materials in a holistic way. Several aspects have been taken into consideration, evaluated through the physical dismantling of both wall systems as well as a LCA assessment. Construction cost as well as other material benefits, such as the hygroscopic performance of construction materials have been investigated as well. The results demonstrate that earthen materials reduce both, construction and demolition waste as well as CO\textsubscript{2} emissions and demonstrate a much higher water vapour sorption capacity, a material parameter relevant for the reduction of mechanical ventilations systems. Although the economical assessment shows expectable lower construction cost for the wall system based on conventional materials such figures have to be placed in relation with the other results. In fact, the analysis demonstrates clearly that a holistic approach is needed in order to achieve the necessary shift.

Keywords. construction product, case study, circular construction, earthen materials, reduction of waste, resource consumption and CO\textsubscript{2} emissions

1. Introduction
The construction sector in Germany is one of the most resource- and CO\textsubscript{2} intensive industries, being responsible for about 55% of the overall waste generation, 92% of the mineral resource consumption and 30% of the CO\textsubscript{2} emissions [4][2][5]. All above the enormous consumption of resources has become clearly visible in recent years, through both, the growing number of construction activities but also through the ever-shorter lifespan of buildings, building components or interior fit-out [6]. On average, around 517 million tons of mineral raw materials are required for the construction and renovation of buildings per year [2]. In return around 230 million tonnes of construction and demolition waste (CDW)
were generated in 2019, due to missing strategies to close such gaps [4]. Solely the production of building materials used for new construction and renovation causes approx. 8% of Germany’s CO₂ emissions [5]. Such figures demonstrate clearly the major role that the construction sector plays regarding the implementation of measures to reduce resource consumption, waste generation as well as CO₂ emissions to effectively mitigate climate change.

In order to close material cycles and to minimise construction related CO₂ emissions, the industry has to rethink the linear way of planning, constructing, operating and deconstructing buildings to enable a direct reuse of building elements or components. The implementation of circular concept starts with the selection of suitable construction materials and a consequent implementation of construction principals that enable the non-destructive dismantling of building components. Low emitting materials, free of harmful substances or chemicals, that enable easy maintenance during operation and a direct reuse and/or high-quality recycling with limited usage of embodied energy at the end of the products lifespan become more and more relevant for applications where renovation cycles become ever shorter, e.g. office or shop fit-out. Earth as intrinsic circular construction material offers unrevealed potential as the material not only enables infinite life cycles due to its reversible binding agent, also the low embodied energy for manufacturing and its hygroscopic properties are important material properties for the implementation of circular concepts [7].

This paper elaborates the technical, ecological, economical as well as health benefits of earthen construction products, namely earth dry boards and earth plasters, to be used for interior fit-out. The reuse potential of earth dry boards and earth plasters as well as associated environmental benefits have been evaluated and assessed against conventional construction products such as gypsum plaster boards. Different assessments (cost, LCA) as well as an experimental deconstruction study have been carried out. The study aims to pave the pathway for architects and planners to provide relevant and holistic arguments in the planning process to overcome decisions in favor of the most economical solution.

2. Materials and general considerations

2.1. Material evolution and areas of application

Earth as one of the oldest construction materials besides timber, has a long tradition in Germany. Being extracted locally with little energy, earth was historically used for solid walls, timber infills (wattle and daub construction), ceiling fillings or plasters (walls and ceilings). Although the material has largely been replaced through industrial manufactured building products at the beginning of the last century, the material experienced a renaissance due to the ecological movement in the 1980’s. Even though the market share has steadily increased, earthen materials still play a negligible role in the overall construction market [8]. In Germany the material nowadays is mainly used as surface finish in form of plasters, thin-layered coatings for walls and ceilings or in dry constructions in form of earthen dry boards, however, also massive wall constructions, such as rammed earth or earthen masonry are becoming more popular.

Earthen materials consist of clay, silt and sand, other mineral or plant-based additives. According to the specific product and its application, the composition of the single ingredients varies. Since 2013 in total four DIN norms have been established for earth plasters, mortars, blocks and boards, however, material properties are not well researched and the material performance not well established in comparison to conventional construction materials [9][10][11][12]. This study focusses on earthen materials for interior application, namely earthen plasters and earth dry boards, that demonstrate within earthen construction relatively high application rates and suggest a high potential for replacement of less ecological, non-reusable construction materials. All investigated construction materials are available on the market.

2.1.1. Earth dry boards. The earth dry boards evaluated in this study, are two different products, manufactured as unfired, flat boards out of clayey soil, clay, silt and sand. Board 1 contains in addition perlites, reed as support structure as well as hemp and jute fibre fabric on both sides as surface
reinforcement. The board is 20 mm thick and characterised by a raw density of 700 kg/m$^3$ and achieves a water vapour sorption class III, according to DIN 18947 [11]. Board 2 is 22 mm thick and contains in addition starch, clay, wood fibres as well as jute fabric on both sides as surface reinforcement. The raw density is with 1.450 kg/m$^3$ almost twice as high in comparison to board 1. Board 2 is also classified in water vapour sorption class III, according to DIN 18947 [11].

Earth dry boards can be applied in various different areas of dry construction such as wall or ceiling cladding as well as paneling for non-load bearing partition walls with a substructure. For the purpose of a reduction of construction times, they can replace earth plasters and can also be used as lost formwork. The earth dry boards assessed in this study were assembled as part of a non-load bearing timber stud partition wall.

2.1.2. **Earth plaster.** The earth plaster assessed in this study is a pure mineral, earth plaster, suitable for application as final coat. The material consists of clayey soil with a grain size up to 5 mm, mixed-grain washed or crushed sand with a grain size between 0 mm and 2.8 mm. The plaster is characterised by a raw density of 2.0 kg/m$^3$, a drying shrinkage of 2% and achieves a strength class II as well as a water vapour sorption class III, according to DIN 18947 [11].

Earth plasters can be applied as single- or multi-layer coating on walls and ceilings internally as finishing coat as well as in weather-protected exterior areas. The earth plaster evaluated in this study was applied onto the earth dry boards, described above, as final coat.

2.1.3. **Benchmark products.** Standard gypsum plaster boards, available on the market were selected as benchmark products. The plaster board contains stucco, starch and foaming agents as additives for the gypsum core, a multi-laminated card board as well as glue. Substances in concentrations above 0.1% by weight, listed in the ‘candidate list of substances of very high concern’ are not contained. The board is 12.5 mm thick and characterised by a raw density > 650 kg/m$^3$ and does not achieve any water vapour sorption class [11][13].

The board can be used as ceiling and attic cladding as well as for suspended ceilings, for stud walls as well as for supplementary planking in renovation areas and dry plaster. The board assessed in this study was a small-scale internal partition wall sample.

2.2. **Potential for circular construction**

Due to its binder, earth is intrinsic circular and can be reused infinite number of times, as long as no additional binder such as cement or lime has been added [7]. Fine, flaky-shaped clay minerals act as natural binder through mutual electrical attraction, once the mixing water has dried out. In comparison to other construction materials or products such as gypsum, cement-, or lime-based plasters, where an artificial binder provokes a chemical reaction and therefore the hardening process, earthen plasters can be replasticised through the addition of water endless times [14]. For the recycling of gypsum or chalk the material has to be crushed and burned again to reactivate the binding forces, which requires much higher amounts of energy in comparison to the addition of water and the required mixing process. Especially for applications, where renovation cycles become ever shorter e.g. for the interior fit-out of offices or shops, earthen materials could help to minimise resource consumption, waste generation as well as CO$_2$ emissions.

In this study, earth dry boards have been assessed regarding a direct reuse, whereas the earth plaster has been assessed regarding their potential of high-quality recycling.

2.3. **Ecological aspects**

The embodied energy of earthen materials is in general relatively low. For earth dry boards only one generic dataset is available on ÖKOBAUDAT that reflects the material properties of board 1 [15]. For earthen plasters the environmental impact relates mainly to the production processes and potentially to the transport rather then to the material composition. Especially the drying process contributes to the environmental effects. Products with natural soil humidity demonstrate the least impact, followed by
products that have been dried with passive solar technologies. Values available at ÖKOBAUDAT are not fully comprehensible, as original data bases are missing [16]. For the benchmarked gypsum plasterboard a product specific dataset is available [17].

2.4. Economic aspects
Material and construction costs are one of the main drivers regarding the decision for or against a building product and/or a construction. The consideration of isolated investment cost often promotes decisions, which in the long run lead to less economic and ecologic results.

2.5. Other material benefits
Earthen materials offer other benefits that are rarely considered when it comes to construction. The indoor air quality of our buildings depends, among others, on the relative humidity levels indoors. According to Scofield and Sterling healthy relative humidity levels range between 40% - 60% as the activity of microbiomes (e.g. viruses, bacteria, fungi) is limited [18]. Studies from Klinge et al indicate that the provision of such a climate relate to the application of suitable materials in combination with an appropriate ventilation concept. Hygroscopic materials are able to adsorb and desorb moisture out of the air. In combination with natural ventilation, they provide stable relative humidity levels [13].

The hygroscopicity of earthen materials are expressed by the water vapour sorption class, defined in DIN 18947 [11]. For conventional construction materials this material property is hardly investigated. For the implementation of circular construction this parameter seems rather important as the need for mechanical ventilation can be reduced, which generally means less use of resources and in addition enables easier and more robust and reversible constructions.

3. Methodology
In this experimental study various different parameters have been assessed that are important within the overall concept of circular construction.

3.1. Potential for circular construction
To evaluate the potential of the presented earthen building materials regarding circular construction, the dismantling process of a drywall system was examined in an experimental study in light of a future reuse and high-quality recycling [19]. For this purpose, a 35 m² interior wall system, which served as a partition wall in an office extension, was dismantled. The existing wall was constructed as a non-load-bearing, timber stud-construction assembled at a grid of 37.5 cm. The studs were lined with earth dry boards, which were screwed with torx headed screws against the wooden substructure and plastered with a 2-layer earth plaster system either side. To avoid cracking, a fabric (for the sake of research jute and glass fibre) was inserted within the 3 mm earth adhesive applied onto the board. As final coating the earth plaster was applied onto the board with a thickness of approx. 10 mm. No further finishes in form of thin-layered plaster or paint were applied.

One year after application, the earth wall system was dismantled following the strategy of selective dismantling in a ‘wet process’, starting layer by layer from the outside to the inside. Firstly, the earth plaster was softened with spray. In a second step the overlaps of the fabric were identified to use the fabric for the separation of the earth plaster from the board (Figure 1 – 2). The earth adhesive was separated with squeegees and scrapers. The joints between the boards were exposed with a scraper. Additional sprinkling helped to identify the position of the screws, that could be uncovered with a cutter and unscrewed in order to dismantle the boards (Figure 3). All materials were collected and kept separately.

For the gypsum plaster boards a small-scale sample was dismantled following the same concept of selective dismantling in reverse order of construction.
3.2. **Life cycle assessment**

The life cycle assessment was carried out for both drywall systems, in accordance with DIN EN 15804 [20]. The functional unit represents 1 m² of internal partition wall system. Noise or fire protection were not taken into consideration. The first wall construction consists of natural building materials (timber studs, wood fibre insulation, earth dry lining board, earth plaster system, silicate paint) and the second one of conventional building materials (metal studs, mineral wool, plasterboard, dispersion paint). The LCA balance was prepared using the free software eLCA of the Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR) and based on datasets available at Ökobaudat, taking into consideration the following life cycle phases: manufacturing (A1-A3), exchange B4 and disposal C3-C4 [21]. Based on the results of the experimental study of the dismantling potential of both wall systems, it was assumed that the wall system based on earthen material and timber studs can be dismantled and reused twice within the study period of 50 years, whereas for the conventional wall system three replacements have been assumed. This reflects current practice and renovation cycles, first of all for commercial buildings. Seven impact indicators were examined in the life cycle assessment.

3.3. **Economical aspects**

The construction cost for the internal wall partition systems have been taken from relevant literature for the wall based on natural building materials and from BKI, the Building Cost Information Center of the German Chambers of Architects for the construction based on conventional building materials [22][14].

3.4. **Other material benefits**

To determine the water vapour sorption class, water vapour sorption tests have been carried out. The test procedure is determined in DIN 18947 to identify the capacity of earth plasters to adsorb moisture from the air via the specimen’s surface within set time intervals [11]. The test requires to pre-condition three material samples (0.1 m³) in a climate chamber at a temperature of (23 ± 1) °C and (50 ± 5)% relative humidity (RH) until constant weight is achieved. The RH level is then increased to 80% and the weight of the samples is measured at specific time intervals (0.5 h, 1 h, 3 h, 6 h and 12 h). Based on the results, the water vapour sorption class of plasters can be classified. The adsorption process is normally
conducted for 12 h, however for wall build-ups the procedure was extended to 5 adsorption/desorption cycles. In the absence of any other suitable test procedure, the test has been applied also to the boards investigated in this study [13].

4. **Results**

4.1. **Potential for circular construction**

The experimental deconstruction studies demonstrated that the earth dry wall could be dismantled completely and almost in a non-destructive manner. The wetting of the earth plaster turned out to be very effective, as the inserted fabric could be used to separate the plaster from the earth adhesive almost completely as single-origin (Figure 1-2). Since two different fabrics (fibreglass and jute) were applied, the dismantling process showed that only the fiberglass fabric was suitable for a direct reuse, as the jute fabric was too deformed. Attempts to separate the earth adhesive from the earth dry board were not expedient as the process was very time-consuming, and the dust exposure was extremely high. Some of the earth dry lining boards broke in the region of the corners. In such cases, the panels were excluded and set aside for further recycling. 96% of the applied screws have been identified for reuse. The earth plaster was separated and air dried. The reconstruction of the wall system is still pending due to organisational constraints.

The dismantling of the gypsum plasterboard failed due to the application of irreversible spatula. Screws could not be uncovered and therefore boards could not be dismantled in a non-destructive manner [19].

4.2. **Life cycle assessment**

As mentioned before, seven impact indicators were examined in the life cycle assessment. The earth dry wall showed significantly better results than the conventional internal wall system for six indicators, especially for the most relevant ones that contribute to climate change, namely the global warming potential (GWP) and the primary energy not renewable (PENRT).

![Figure 4. Life cycle assessment of two interior wall systems](image)

The GWP was 98% lower whereas the PENRT was 98.5% lower for the wall system based on earthen and timber building materials (wall 1) in comparison to the conventional wall system (wall 2). The
photochemical ozone creation potential (POCP) was 66% lower, the acidification potential (AP) was 76% and the eutrophication potential was (EP) was 70% lower for wall 1. Only for the ozone depletion potential (ODP) the value for wall 1 was significantly worse as for wall 2. Although the difference in performance of 2.828.730% seems extremely high, the overall impact of this indicator is less than 1 g/m² over 50 years. Figure 4 shows the indicators examined and the results of the assessment [19].

4.3. Economical aspects
The amount of data available on the cost of earthen construction is relatively limited. Extreme values can have a strong influence on the average value provided. Figures provided have to be reflected with great care. For standard drywall construction based on gypsum plasterboards the data available are more robust, due to the long tradition of this construction. However, in both cases current price developments due to material shortages and the interruption of supply chains are not reflected. The material- and construction cost for the earth dry board wall, plastered with earth plaster have been established with approx. 105€ - 120€/m², whereas the cost for a standard gypsum plasterboard wall have been established with approx. 54,50€ - 61,50€ [22][14].

4.4. Other material benefits
The water vapour sorption test demonstrates the outstanding water vapour ad- and desorption capacity of the earth drywall system in comparison to the standard gypsum plasterboard wall. Already after the first cycle the capacity is 3 times higher, whereas after the fifth cycle the difference sums up to 115 g/m², which is almost 5 times higher. In addition, the measurement clearly show that the sorption capacity of the gypsum plasterboard is almost saturated after the first cycle, whereas the earth dry board construction also after the fifth cycle has not reached the maximum adsorption capacity. Figure 5 shows the results from the water vapour adsorption test [13].

![Water vapour adsorption test of two partition wall systems](image)

**Figure 5.** Water vapour adsorption test of two partition wall systems

5. Discussion

5.1. Potential for circular construction
The experimental study demonstrated the very high reuse potential of earth dry walls. A prerequisite for this is the use of a selective dismantling method. The amount of waste could be reduced to nearly zero, as even broken panels and non-reusable screws can be recycled (Figure 5). The recycling potential of
the jute fabric needs further investigation. The study shows that primary raw material consumption, waste generation as well as associated CO₂ emissions can be significantly reduced [19].

The reuse potential for the gypsum plaster board wall was very low, due to the non-reversible spatula applied. Recycling would be an option to be explored. However, in Germany there is only one recycling plant for gypsum, which is located in the middle of Germany.

**Figure 6.** Amount of waste from dismantling process of 35 m² earth dry wall

5.2. *Life cycle assessment*

The outstanding results of the life cycle assessment for wall 1 relate to both the very limited ecological impact of earthen building materials and the carbon storage capacity of the timber stud system as well as to the reuse potential of the entire wall construction. For wall 2, the CO₂ emissions of the materials are higher and in addition, three replacement cycles have been assumed, due to lacking reuse potential. The study underlines the importance regarding the suitable material selection as well as the need for reversible construction.

According to the RESCU study published by the Federal Environmental Agency, that investigated pathways for Germany to become climate neutral by 2050, resource consumption needs to be reduced by 60% and CO₂ emissions by 95% [23]. In that respect the results underline the potential of natural building materials to meet such ambitions goals and put the higher investment costs of this type of construction into perspective. The result of the ODP is logically incomprehensible, to the point that we have called it into question and are currently discussing it with the BBSR (publisher of the Ökobaudat). It is assumed that the value relates to the packaging material of the wooden components. An update of the data set is urgently required [19].

5.3. *Economical aspects*

The material- and construction cost for the earth dry wall construction are nearly twice as high per m² as for the standard gypsum plasterboard wall. However, this cost assessment does not reflect the material value of the reusable wall components neither the reduced cost for smaller mechanical ventilation systems and reduced maintenance cost in relation to the mechanical ventilation system nor any related cost for the environmental impact of the construction.

5.4. *Water vapour sorption*

The outstanding adsorption and desorption capacity of earthen materials is a material property that has to be investigated further in light of circular construction. Under the EU-funded research project [H]house it has been established that earthen materials enable lowtech construction and minimise the need for mechanical ventilation systems, while providing healthy indoor environments [13].

6. **Conclusion and outlook**

The experimental study and the life cycle assessment show the outstanding potential of earth building
materials for circular construction and make it clear that the use of high-quality building materials and construction methods can significantly reduce the amount of waste generated by the construction sector [19]. It is desirable that LCA studies should reflect Module D and include the benefits of the reuse potential of materials and constructions within the final results. In such way, more holistic results can be displayed and solutions that minimise resource consumption and CO₂ emissions will be promoted. The cost assessment purely based on construction cost demonstrates that life cycle costing is important to apply eco-friendly and circular construction. Life cycle costing should however include the material value generated through the concept of circular construction and also reflect cost for environmental damages that are currently shifted to the society.

The finalisation of the experimental study with regards to reassembly is important to complete the assessment and the verify the results. Earth plasters should be tested against the mandatory tests set out in [11] in order to verify the required material performance.

Limitations of the study relate to its extend, as the initial examination the was carried out as experimental study. In order to increase the impact of the results, additional practical assessments would be desirable.

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