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The ecological life cycle assessment of earth building materials

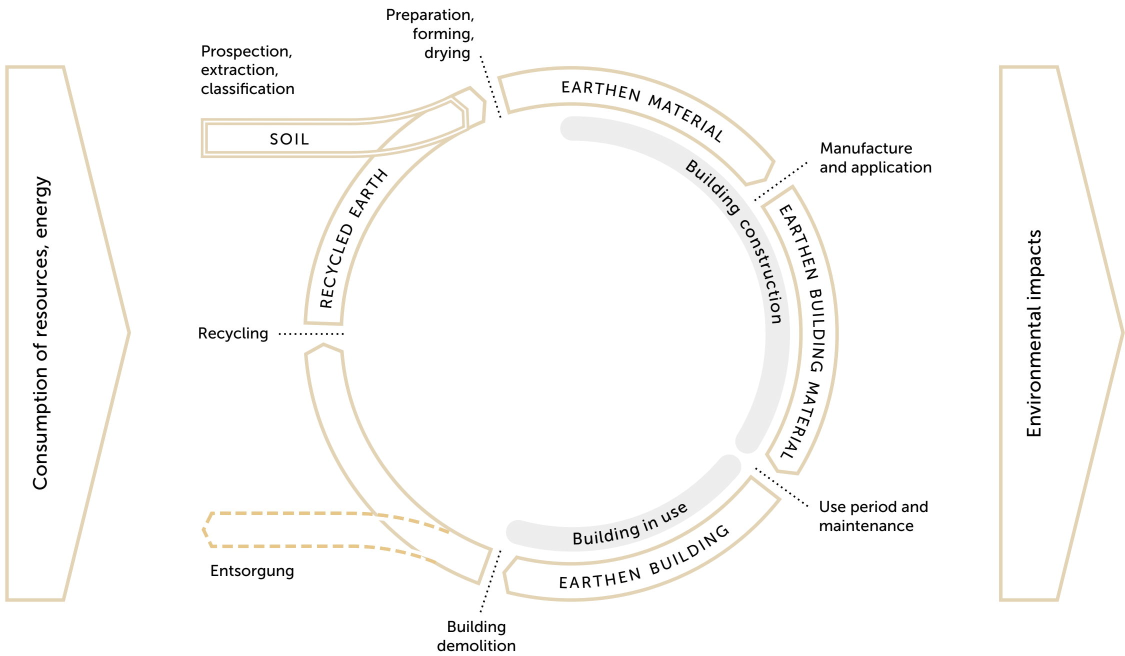
The climate action programme adopted by the German Federal Government in October 2019 includes the goal to reduce greenhouse gas emissions by at least 40% by 2030 compared to 1990 levels. To achieve this goal, a national emissions trading system (nETS) will be introduced in which producers of carbon emissions will need to pay 10 euros per tonne of CO_2 emissions, rising to 35 euros per tonne by 2025 and up to 65 euros in future.

All construction-related processes contribute significantly to greenhouse gas emissions and the new carbon pricing scheme will (also) require the construction industry to comprehensively review the sustainability of the process chains for the production of building materials, for construction, building operation and maintenance, demolition and recycling of buildings and building materials.

Today, ecological balance analysis is a generally accepted methodological approach to quantitatively analysing the sustainability of (building) products. In recent years, a system of DIN, EN and ISO standards has been developed that are essentially based on the *material cycle/life cycle assessment* (LCA) of the building materials used in a building.

As part of the two-year "UPD Lehm" project which ran from 2016 to 2018 and was funded by the German Federal Foundation for the Environment (DBU), the Dachverband Lehm e.V. (DVL) created a standard-compliant framework for the development of a set of rules for the ecological assessment of earth building materials [1] [2]. The "UPD Lehm.2" project [3a] – also funded by the DBU – began in April 2020 and continues the work undertaken in the initial project.

01 Material life cycle of earthen building materials



The life cycle assessment of earth building materials

Figure 1 shows the model of a building process as a life cycle analysis (LCA) for buildings made of earthen building materials [3] [4]. The entire life cycle of a building takes the form of an inventory analysis (eco-balance), starting with the extraction of raw materials and their provision, through the processing of these materials into building materials, their processing into building components and structures, the use of the building and its maintenance, right up to the demolition and recycling of the building, including the various transport routes in between and the accompanying material and energy flows.

The ecological quality of a construction process is assessed by comparing the resource consumption of the product system and the material flows that leave the system and have a corresponding environmental impact (Figure 1).

The quantified, environment-related information on the life cycle of a product is specified in a standardised form outlined in DIN EN ISO 14025 and DIN EN 15804 as so-called Product Category Rules (PCR) and Environmental Product Declarations (EPD). These contain specific parameters defined in the standards and are drawn up by one or more organisations. They are based on independently verified data from life cycle assessments (type III EPD) and are managed by a programme operator.

While PCRs and EPDs are already available for most mineral-based solid construction materials, they were previously lacking for earth building materials which put earth building material producers at a competitive disadvantage in tendering procedures. The aim of the DVL "UPD Lehm" project [1] was therefore to close this gap by create a framework for the preparation of EPD for earth building materials. Thanks to renewed funding from the DBU, this work is now being continued in a follow-up "UPD Lehm.2" project [3a] that will run until 2022.

A standardised set of rules for preparing life cycle assessments of earth building materials

The framework [2] developed as part of the DVL "UPD Lehm" project consists of:

- four PCR for the building material categories earth bricks (LS), earth masonry mortar (LMM), earth plaster mortar (LPM) and earth building boards (LP) according to DIN 189421, 18942-100, and DIN 18945 – 18948,
- an EPD for earth plaster mortar (LPM). The forthcoming EPDs for earth masonry mortar (LMM), earth bricks (LS) and earth building boards (LP) are the subject of the project "UPD Lehm.2" [3a],
- the "General guidelines for the preparation of life cycle assessments for earth building materials (Part 2)",
- the "General Programme Instructions" which details the specific tasks of the individual parties and the organisational structure of the programme.

Table 1 Balance scheme for the UPD life cycle phases according to DIN EN 15804

Production			Construction		Use stage					End of life stage				B / L*
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	D
Raw materials supply	Transport	Manufacturing	Transport	Construction/installation	Use	Maintenance	Repair	Replacement	Refurbishment	Deconstruction/demolition	Transport	Waste processing	Disposal	Reuse, recovery, recycling potential

B6	Operational energy use
B7	Operational water use

*Benefits / Loads

Modules quantified as part of the LCA of the DVL project [1]

The framework applies the relevant standards for life cycle assessment (DIN EN 15804, DIN EN ISO 14025, DIN EN ISO 14040, DIN EN ISO 14044, CEN ISO/TS 14071) to earth building materials. These are defined in the *Lehmbau Regeln* [3b] and in DIN 18945 to DIN 18948.

Product system

A product system is a set of relevant process modules with associated elementary or product flows that describe the basic life cycle of the product from the provision of raw materials to disposal/recycling in the form of process or information modules (IM). For building products, the balancing scheme according to DIN EN 15804 shown in Table 1 is used, which consists of four life cycle phases to be declared: production (A1–A3), construction (A4–A5), use (B1–B7) and disposal (C1–C4), as well as a phase D for benefits/loads resulting from the product's re-use and recycling potential.

This scheme was used to develop a sample EPD for earth plaster mortar (LPM) as part of the DVL project "UPD Lehm" [1]. Data from the participating product manufacturers revealed different production processes (A1 – A3) with regard to the delivery state of LPM: one earth-moist and three different drying processes:

In the *"naturally-moist"* delivery state, the water content earth remains largely unchanged throughout the entire production phase (IM A1 – A3). The production of LPM includes the process modules "crushing of the extracted earth", "dosing of the raw materials", "mixing" and "packaging/storage".

LPM that is delivered in a *"dry"* state always involves an artificial drying phase, which can take place at various points in the production process. An analysis of the product systems of the LPM manufacturers participating in the DVL project [1] revealed the following drying processes:

- *Post-drying process:* Production as per "naturally-moist" LPM but with final drying (e.g. in a drum dryer),
- *Pre-drying process:* The separate pre-prepared raw materials are actively dried and mixed by the manufacturer according to a defined recipe and delivered "dry", i.e. in powder form.
- *Solar drying process:* Production as per "naturally-moist" LPM with subsequent passive solar drying (e.g. greenhouse effect with ventilation).

These individual processes differ significantly in terms of their energy balance and impact analysis.

System boundaries

The system boundary defines which process/information modules (IM) are part of the product system. DIN EN 15804 distinguishes between three different ways of defining system boundaries for the composition of process modules, the selection of which must correspond to the objective of the analysis:

- "from cradle to factory gate" (IM A1 – A3),
- "from cradle to factory gate with options" (IM A1 – A3 with selected options), and
- "from cradle to grave/cradle" for the entire life cycle (IM A1 – D).

The life cycle assessment can vary accordingly.

Table 1 shows the information modules considered in the DVL "UPD Lehm" project [1] within the selected system boundaries "from cradle to grave/cradle with options" (A1 – A3, C3, D).

The "disposal" stage (C1 – C4) is considered in terms of two properties: recyclability and disposal properties. In terms of sustainability, a building material is ideally recyclable. This presupposes that the original constituent building materials (e.g. earth and sand) can be separated, as well as the respective building component layers from one another.

In accordance with the Closed Substance Cycle Waste Management Act (KrW-/AbfG), recycling waste has priority over disposal. The inventarisation of the "disposal" stage is difficult due to the current lack of data and is therefore often not taken into account in the life cycle assessment. For earth building materials, however, it is relevant and is therefore presented in the DVL "UPD Lehm" project [1] in the form of assumed scenarios.

Functional unit

Functional units for earthen building materials are defined in DIN 18945 to DIN 18948 and in the corresponding PCR/EPD [2] and are shown in Table 2.

Table 2 Functional units for earth building materials defined in DIN 18945-48

Product system (earth building material)	**System performance**	**Functional unit**	**DIN**	**DIN Appendix**	**PCR**	**EPD**
Earth blocks LS	Provision of a defined mass of material	kg LS	18945	A.2	•	
Earth masonry mortar LMM	Provision of a defined mass of material	kg LMM	18946	A.1	•	
Earth plaster mortar LPM	Provision of a defined mass of material	kg LPM	18947	A.2	•	•
Earth building board LP	Provision of a defined quantity of a component	m^3 LP	18948	A.3	•	

Reference service life

For the DVL "UPD Lehm" project, the RSL information was taken from the Bau-EPD catalogue published by the Bau-EPD GmbH [5]. For example, earth mortar, earth plaster mortar and earth bricks have an RSL of 100 years and earth building boards of 50 years.

Assumptions and estimates

The project evaluated operational data provided by the participating manufacturers, including the extraction of the respective raw materials used for the product recipe, the energy input for the production and drying processes, the thermal energy used, the fuel consumption for all internal processes, e.g. transport to and within the plant and for packaging. The energy types and sources used at the production sites were taken into account for the energy resources used.

Primary pit soil is excavated specifically for the production of earth building materials (assumption: the environmental impact of the entire extraction operation conforms to ECOINVENT 3.2 [10] [11]). *Secondary pit soil* is a waste product of clay/sand/gravel extraction (A1) and is provided as a raw material (assumption: the environmental impact of the "excavation" process module conforms to ÖKOBAUDAT [6]). All the remaining extraction processes concern the primary raw materials sand or gravel. For the extraction of earth (naturally moist, moderately cohesive, stiff consistency, extraction class GK 3–4 according to DIN 18300:2012-09 = easy to moderately difficult to extract soils), a wet bulk density of the clay of ρ = 2,000 kg/m^3 was assumed.

Packaging: Bulk woven PP bags and kraft paper sacks (without PE inlet) are evaluated in the EPD for factory mortar [7] with a primary energy content (PET) of 0.01 MJ/kg mortar. This assessment was adopted in the EPD for earth plaster mortar. The environmental impact categories of both types of packaging were derived from an LCA study on earth plaster mortar [8].

Plant particles: The EPD for construction straw was applied [9]. While it does not consider the recovery potential, it does detail the embodied CO_2.

Waste management (C3): To estimate the expected environmental impacts, two different scenarios were considered: a wet and a dry process.

The *wet process* of recovering LPM from unmixed recovered waste LPM (primary recycled earth) is based on the process module "gravel washing" used in gravel extraction: the fine mineral grains contained in the LPM are separated from the gravel grain in a washing plant. The "pressed earth" residue (sand, silt and clay) produced in the process is deposited in landfills. The "gravel extraction" process module detailed in ÖKOBAUDAT [6] was used for the data basis.

The *dry process* of recovering LPM is based on the assumption that the old LPM (*primary recycled earth*) is crushed in impact mills for reuse as LPM. This process is common in building material recycling but can also be used to crush solid lumps of earth in the processing of construction soil. The required energy input was determined from the manufacturers' data and evaluated according to the German electricity mix (ÖKOBAUDAT [6]).

Unmixed recovered LPM can also be used to separate out sand and gravel particles using both processes, e.g. for producing concrete (*secondary recycled earth*).

A third known recovery process – the soaking of unmixed recovered LPM – is common practice in the conversion and extension of old buildings (especially in self-build contexts). After being left to soak for a while, sand can be added as necessary as a leaning agent and stirred in thoroughly. The old LPM can then be reused directly. The ability to replasticize recovered LPM – a product of the hydraulic properties of clay minerals – is a unique selling point of non-stabilised earth building materials. There is no data available to date on this process because it does not generate any significant energy and material flows. The assumption is that the use of this "new" recovered LPM represents a potential ecological benefit (D).

Recovery potential (D): Evaluates the benefit as a calculated savings potential of the mineral raw materials secondary pit earth and undried sand according to the data given for the raw material supply in A1. The assessment is based on a calculated material mass loss of 5 % for both scenarios.

Data collection

Data collection must be conducted according to the instructions in DIN EN ISO 14044, Annex A and the resulting data forms the basis for the impact assessment.

The data required to quantify the consumption of resources and the corresponding environmental impacts across the life cycle of a building product can be obtained in two ways:

- as primary/*specific data* by gathering data from the actual manufacturing plant where product-specific processes are carried out (e.g. through surveys),
- as secondary/*generic data* by using generic data sources (e.g. from commercial databases).

To obtain "specific data" for the model EPD for LPM [1], a standard-compliant survey of material and energy flows and transport routes in the manufacturing plants was developed and sent to the product manufacturers. The collected specific data (reference year 2017) as well as the generic data from data sets and other sources were summarised, calculated and presented graphically. In the DVL "UPD Lehm" project [1], the basic modules shown in Table 3 were used as generic data sources.

The data collected from the product manufacturers showed that the process technology used to manufacture the product is the decisive factor for environmental impact and not the composition of the earth plaster mortar in the respective formulations. Another factor that can play an even greater role is the transport of raw materials. The product data collected from the participating manufacturers covered all known process technologies for earth plaster mortars (and earth masonry mortars).

Use of resources

The total primary energy use of PET (input/renewable and non-renewable) and the associated environmental impact factors (output) are made up of the manufacturer's data on material composition, energy quantity and type, transport to and from the plant and packaging in accordance with the data quality

Table 3 Generic data sources used in the DVL project "UPD Lehm" [1]

No.	Data	Moist	Dry	Generic data source	Ref. year
1	Pit soil		•	Ecoinvent 3.2 full pit operation [10]	2015-11
2	Pit soil as secondary raw material	•		ÖKOBAUDAT 09.01.01 [6]	2018-06
3	Dry earth		•	ÖKOBAUDAT 1.1.04 [6]	2018-06
4	Sand 0/2 – 0/4 not dried	•	•	Ecoinvent 3.2 [10]	2015-11
5	Sand 0/2 – 0/4 dried		•	ÖKOBAUDAT 1.2.04 [6]	2018-06
6	Straw		•	EPD FASBA [12]	2014-10
7	Electricity DE water power; river water	•	•	Ecoinvent 3.2 [10]	2015-11
8	Electricity DE Energy mix 2015		•	ÖKOBAUDAT 9.2.05 [6]	2018-06
9	Packaging PE big bag (1,6 kg/1.200 kg LPM)	•		DIBU IWM and BRE [9] [11]	2008-04
10	Packaging Kraft paper sack (90g/25 kg LPM)		•	DIBU IWM and BRE [9] [11]	2008-04
11	Transport to the plant (35-40 t, EURO 5, 27 t vehicle load, 85% capacity)	•	•	ÖKOBAUDAT 9.3.01 [6]	2018-06
12	Transport within the facility (diesel)	•	•	ÖKOBAUDAT 9.2.03 [6]	2018-06
13	Waste processing	•	•	Ecoinvent 3.2 [10]	2015-11
14	Recycling potential	•	•	Ecoinvent 3.2 [10]	2015-11

Table 4 Indicators of resource use in earth plaster mortar production (A1–A3, process types) [1]

			Process type as per earth plaster mortar EPD [1]			
No.	**Indicator** (annual mean, ref. unit 1 kg mass)	**Unit**	**Moist**	**Post-dried**	**Pre-dried**	**Solar dried***
1	PERE: Renewable PE as ET	MJ	3.58E-02	4.00E-02	8.13E-02	2.73E-02
2	PERM: Renewable PE used as raw materials	MJ	7.23E-09	7.23E-09	1.27E-01	6.34E-02
3	**PERT: Total use of renewable PE**	MJ	**3.58E-02**	**4.00E-02**	**2.08E-01**	**9.08E-02**
4	PENRE: Non-renewable PE as ET	MJ	1.14E-01	1.09E+00	8.62E-01	1.35E-01
5	PENRM: Non-renewable PE used as raw materials	MJ	0	0	3.78E-04	1.89E-04
6	**PENRT: Total use of non-renewable PE**	MJ	**1.14E-01**	**1.09E+00**	**8.62E-01**	**1.35E-01**
7	**Total PET = PERT + PENRT**	MJ	**1.50E-01**	**1.13E+00**	**1.07E+00**	**2.26 E-01**

passive solar drying

described above. Table 4 quantifies the indicators for describing the use of resources for the production of LPM, subdivided by process type into soil moisture process, post-drying (after soil moisture production), pre-drying (mixing of dry components) and passive solar use (ventilated greenhouse).

Due to the "grey" energy (amount of energy required for the manufacture, transport, storage, sale and disposal of a product) in the preliminary products dry clay and dried sand grain, the PET for the *pre-drying process* with a total of 1.07 MJ/kg LPM increases significantly in comparison with the earth-moisture process (0.15 MJ/kg LPM) and passive solar drying (0.23 MJ/kg LPM). The grey energy contained in dry clay with a proportion of 0.472 MJ/kg or 44% is taken from ÖKOBAUDAT [6]. However, the basis for calculation is not comprehensible. It is based on the homepage of a Berlin crafts enterprise from 2008, where original data are missing.

In the *post-drying process* (following the soil moisture process), the use of liquid gas for drum drying results in a significantly increased total energy input of PET of 1.13 MJ/kg LPM. In the solar drying process in the greenhouse, it is mainly diesel and electricity consumption that causes the energy consumption of 0.22 MJ/kg LPM.

All production processes for LPM do not require any water supply. The mixtures are made earth-moist with a natural moisture content w = 4–13% or dry. The energy consumption of the packaging collected is taken from the EPD factory mortar for equivalent types of packaging and is assessed at 0.01 MJ/kg LPM.

Impact assessment

In accordance with the life cycle assessment guidelines drawn up by the DVL [2], Table 5 shows the environmental impact indicators used to describe and quantify the environmental impacts. All indicator values were taken from domestic or foreign databases.

It quickly becomes clear that post-drying the raw materials entails greater CO_2 emissions (Global Warming Potential, GWP) than naturally moist processes. There is, however, potential for ecological optimisation, for example by using greenhouse drying. Because extraction and production of the naturally moist base material is relatively energy-efficient, the GWP of greenhouse-based post-drying processes remains relatively low (0.0152 kg CO_2 eq./kg earth plaster mortar) despite the higher energy input (Abiotic Resource Depletion Potential for fossil fuels, ADPF: 1.16 MJ/kg earth plaster mortar).

Pre-drying and mixing the raw materials results in a higher GWP of 0.124 kg CO_2 eq. and this value already includes a credit for the straw portion (1.1%) of -0.014 kg CO_2 eq. and the kraft paper packaging (90 g) of -0.00245 kg CO_2 eq.

Passive solar drying leveraging the greenhouse principle results in a calculated negative GWP of -0.00178 kg CO_2 eq. This example also shows the ecological relevance of the low plant content (0.5 % composition by mass). The calculated value includes credits for the plant fraction amounting to -0.00636 kg CO_2 eq. If one disregards this, the GWP value increases by 360% to -0.00458 kg CO_2 eq., clearly illustrating the ecological relevance of the plant fraction in the earth plaster mortars under consideration. For

Table 5 Environmental impact indicators of earth plaster mortar production (A1-A3), process types [1]

			Process type as per earth plaster mortar EPD [1]			
No.	**Indicator** (annual mean, ref. unit 1 kg mass)	**Unit**	**Moist**	**Post-dried**	**Pre-dried**	**Solar dried***
1	GWP: Global Warming Potential	kg CO_2 eq.	6.,92E-03	1.52E-02	1.24E-01	-1.78E-03
2	ODP: Depletion pot. of stratospheric ozone layer	kg R11 eq.	2.68E-10	2.73E-10	8.52E-11	5.54E-10
3	POCP: Formation pot. of tropospheric ozone	kg Ethylene eq.	3.58E-06	1.21E-05	1.64E-05	6.72E-06
4	AP: Acidification potential of land and water	kg SO_2 eq.	1.70E-05	7.91E-05	1.80E-04	5.08E-05
5	EP: Eutrophication potential	kg PO_4 eq.	4.85E-06	8.70E-06	3.11E-05	1.26E-05
6	ADPE: Abiotic res. depletion pot. for elements	kg Sb eq.	3.59E-07	2.89E-06	8.99E-06	2.19E-06
7	ADPF: Abiotic res. depletion pot. of fossil fuels	MJ	1.35E-01	1.16E+00	8.84E-01	1.56E-01

passive solar drying

this reason, proportional plant contents of less than 1 % composition by mass were included in the balance. Earth plaster mortars prepared as naturally moist material and then post-dried do not contain any plant matter.

Evaluation of the project results

The life cycle assessment of earth plaster mortars made it possible to undertake a differentiated and comprehensive standards-compliant evaluation of the environmental impact of earth building materials for the first time. The detailed examination of the processes identified in the production of earth plaster mortars also made it possible to detect weaknesses and potentials for ecological improvement: for example, appreciable benefits can be made in the area of transport within the facility (e.g. using wheel loaders, forklift trucks, etc.). The positive environmental impact of innovative drying processes, for example by leveraging passive solar energy use, was also shown.

Energy and environmental balance of plaster mortars

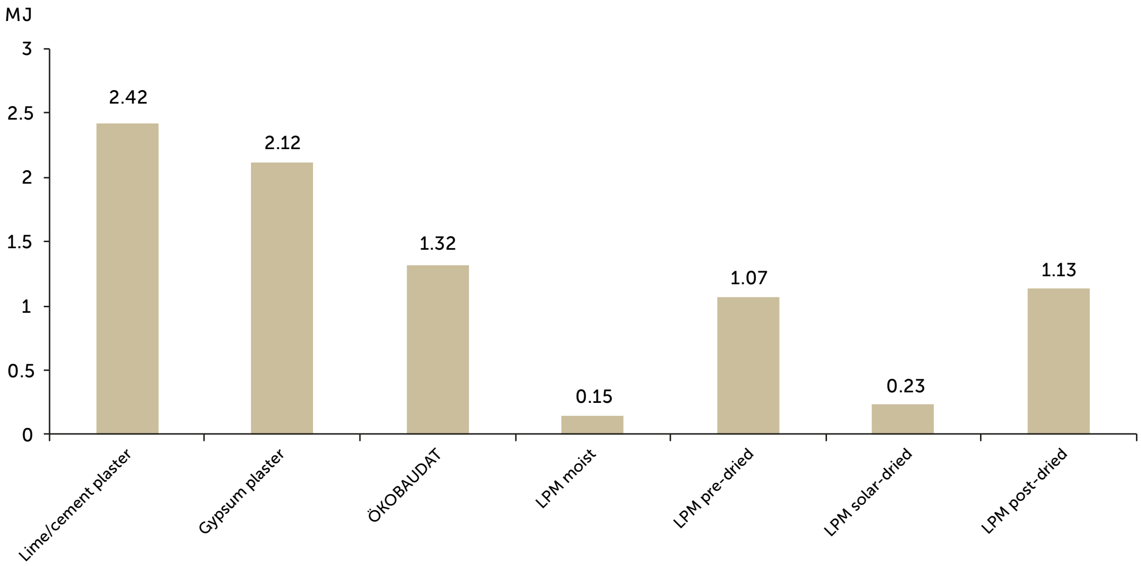
To classify the energy and environmental balance of earth plaster mortars, the total primary energy input (PET) and the greenhouse effect (CO_2 eq.) are compared against the corresponding values of common mineral plaster mortars. In addition, the specific data determined in the project [1] are compared against generic values published in the official database of the Federal Ministry of Building (ÖKOBAUDAT [6]).

The total primary energy consumption PET covers the production phase (A1 – A3) including packaging. Figure 2 shows the PET values of the four production processes investigated: naturally moist, pre-drying with mixing of the dry raw materials, passive solar drying (greenhouse drying) and post-drying of naturally moist earth plaster mortar (here: using liquid gas).

When compared against the EPDs of lime, cement and gypsum plasters, the energy requirement of the naturally moist and solar drying processes is 10 times lower. Even the more energy intensive pre- and post-drying production processes for earth plaster mortars consume approx. 50% less energy than other mortars. However, the grey energy of the dried preliminary products and the use of liquid gas lead to an increase in resource consumption compared to the other two production processes.

One can also see a clear discrepancy between the official generic values in the ÖKOBAUDAT [6] database and the actual data recorded and calculated for the earth plaster mortar samples in the EPD [2], as the ÖKOBAUDAT database specifies all earth plaster mortars as consuming 1.32 MJ/kg independent of the production process.

The global warming potential GWP of the naturally moist and solar drying production processes for earth plaster mortars shown in Figure 3 is significantly lower than that of other plaster mortars by a factor of two powers of ten. With the naturally moist production process, this is a product of the use of secondary construction soil from gravel extraction and the low electricity requirements, provided by green electricity from hydropower. With the solar drying process, the use of passive solar energy through the greenhouse effect and the short distance to the excavation pit also lowers the GWP values. The negative values are



02 Comparison of the total primary energy input PET of common mineral and earth plaster mortars

a product of credits for the inclusion of straw and paper bags. Without these credits, the GWP value of the solar drying process is in the order of magnitude of the naturally moist process (0.003 kg CO_2 eq.).

The GWP value for the pre-drying process is noticeably higher at 0.12 kg CO_2 eq. but it should be noted that this value is based on inadequate data from the ÖKOBAUDAT [6] for dried earth that is specified as 0.14 kg CO_2 eq./kg. The data basis for dry earth is therefore only a first approximation. Further research and evaluation into this preliminary product is necessary.

Availability of raw materials

As "geologically evolved" natural materials, all mineral raw materials are generally limited in their availability. The majority of the earth plaster mortars covered by the EPD are made of suitable clay-rich excavated soils from local earthworks (e.g. gravel and sand extraction, lime mining, civil engineering). i.e. have been processed as a secondary raw material (= secondary pit earth).

Some 128 million tonnes are excavated each year and constitute the greater proportion (64%) of the total mineral construction waste in Germany [1]. By recycling clay-rich excavated earth as a secondary raw material for earth plaster mortars and other clay building materials saves landfill space and extends the availability of primary raw materials. Due to the special properties of clay as a binding agent, earth plaster mortars can also be replastified and reused at any time. There is therefore no shortage of raw materials.

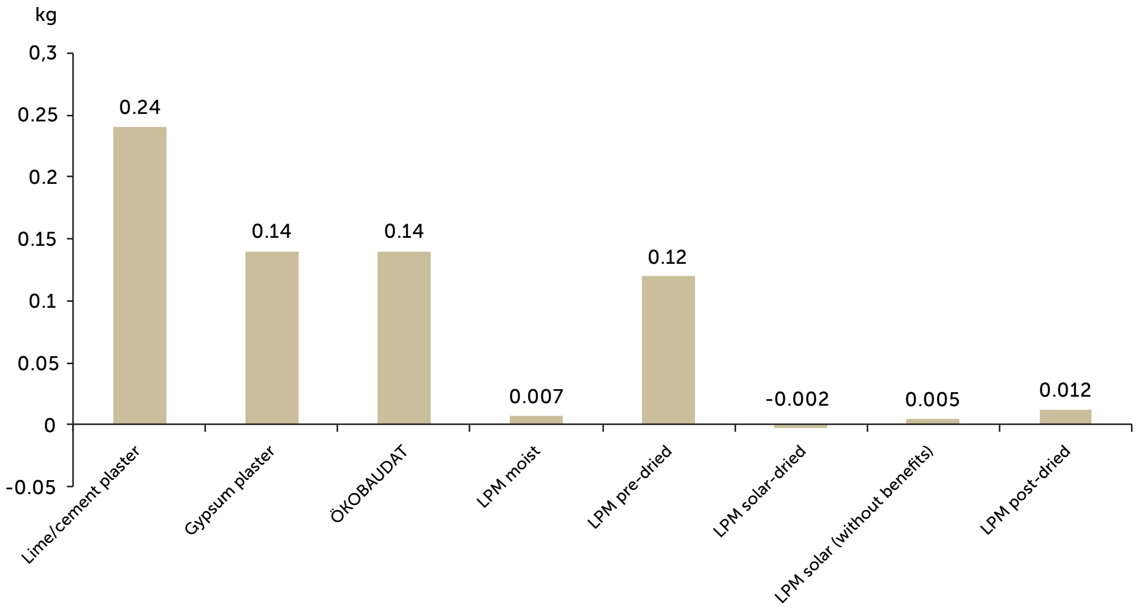
Reusability of earth plaster mortar

The project [1] has revealed new findings on the reusability of earth plaster mortars and other earth building materials. The fact that hardened material can be replasiticized at any time contributes to its reusability and is an important ecological evaluation criterion. A further aspect is the availability of the raw material and the components bound within the earthen building material, e.g. sand, lightweight aggregates and plant fibres.

In the conversion and extension of old buildings (especially in self-build contexts), the soaking of (cleanly separable) recovered earth masonry mortar is common practice. After being left to soak for a while, sand can be added as necessary as a leaning agent and stirred in thoroughly. The old earth mortar can then be reused directly. The ability to replasticize recovered LPM – a product of the hydraulic properties of clay minerals – is a unique selling point of non-stabilised earth building materials. There is no data available to date on this process because it does not generate any significant energy and material flows.

According to DIN 18947, earth plaster mortars are usually reinforced with jute fabric or glass fibre mesh during application. During renovation or demolition these fabric meshes can be manually removed together with the earth plaster mortar adhering to it from the underlying building structure. Soaking makes it possible to separate the mortar from the mesh.

Two processing scenarios were developed (C3) for which the expected environmental impacts were es-



03 Comparison of the global warming potential GWP of common mineral and clay plaster mortars

timated and compared against the quantified recovery potential (D). To date there are no industrial recovery systems for earth building materials, but with the increasing uptake in earth building materials and the foreseeable end of use phase of many old buildings with earth building elements, this aspect of recovery may become more important in the future.

The *wet process* of recovering mineral grains, e.g. sand, silt und clay, from unmixed recovered earth mortar is comparable to the process of "gravel washing" used in gravel extraction. The "pressed earth" [3] residue produced in the process is usually deposited in landfills. The "gravel extraction" process module detailed in ÖKOBAUDAT [6] was used for the data basis. The wet process assumes that on average 15% of clays or silt and 85% of sand can be recovered, but no plant material. A 5 % mass loss is assumed.

The *dry process* of recovering LPM is based on the assumption that the old LPM (primary recycled earth) is crushed in impact mills for reuse as earth plaster mortar. Such mills are usuall used to recycle materials but they can also be used to crush solid lumps of earth in the processing of construction soil. The required energy input was determined from the manufacturers' data and evaluated according to the German electricity mix (ÖKOBAUDAT [6]).

Table 6 details the indicators "resource use" (C3) and "recovery" (D) for both processes. A comparison of the total primary energy input and the recovery potential reveals an ecological gain for both processes in the range of -0.0222 MJ/kg to -0.0145 MJ/kg as *recycling potential* (PET processing – recovery). While this does not include the transport cost of reprocessing, it dies quantify possible "ecological margins" for the logistics of earth mortar reprocessing. The transports from reprocessing to the factory gate is again included in modules A1 and A2 as raw material transport for a new production cycle.

Table 7 shows the environmental impact indicators for both methods. The ratio of preparation work (C3) to recovery potential (D) depends on the processing technologies used and the assumed recovery rates. The wet process includes a 5 % mass loss and a separation of the raw materials according to a typical sieve analysis, i.e. approx. 15 % composition by mass of clay and silt and 85 % composition by mass of sand and gravel grains. In the dry process, the earth mortar recovered is only crushed and recycled without further separation or washing. The impact mills used operate with an average consumption of 0.003 MJ/kg electrical energy. The results of these first exploratory scenarios gave rise to further analyses of technical possibilities for processing and activating the recycling potential of earth plaster mortars.

Experimental studies on the reusability of earth plaster mortar

In response to the DVL "UPD Lehm" project [1], experimental studies on the reusability of earth plaster mortars were carried out in 2018 as part of a diploma thesis at the Department of Civil Engineering (Prof. Dr.-Ing. Klaus Pistol) at Potsdam University of Applied Sciences [13] [14].

Table 6 Indicators: Resource input PET (C3) and recovery (D) [1]

			Scenarios			
			Wet process		Dry process	
No.	**Indicator** (annual mean, ref. unit 1 kg mass)	**Unit**	**Module C3**	**Module D**	**Module C3**	**Module D**
1	PERE: Renewable PE as ET	MJ	1.07E-02	-4.71E-03	1.18E-02	-3.39E-03
2	PERM: Renewable PE used as raw materials	MJ	0.00E+00	1.11E-08	0.00E+00	-7.84E-09
3	**PERT: Total use of renewable PE**	MJ	**1.07E-02**	**-4.71E-03**	**1.18E-02**	**-3.39E-03**
4	PENRE: Non-renewable PE as ET	MJ	3.82E-02	-4.64E-02	2.15E-02	-4.44E-02
5	PENRM: Non-renewable PE used as raw materials	MJ	0.00E+00	0.00E+00	0.00E+00	0.00E+00
6	**PENRT: Total use of non-renewable PE**	MJ	**3.82E-02**	**-4.64E-02**	**2.15E-02**	**-4.44E-02**
7	**Total PET = PERT + PENRT**	MJ	**4.89E-02**	**-5.11E-02**	**3.33E-02**	**-4.78E-02**

Summary

This article explained the procedure and the results of the development of a standard-conforming framework for the preparation of PCR/EPD for earth building materials carried out in the framework of a DBU-funded project carried out from 2016 to 2018. As part of this the Dachverband Lehm e.V. (DVL) developed the first set of product category rules (PCR) for earth building materials on the basis of the existing DIN 18945 to DIN 18948 and in turn the normative and organisational prerequisites for preparing corresponding environmental product declarations (EPD). An EPD was drawn up and published for earth plaster mortars in accordance with DIN EN 15804 on the basis of data collected from product manufacturers. The DVL acts as the programme operator.

The data collected from the manufacturers of earth plaster mortars provided insight into the current predominant production processes of "naturally moist" or "dry" earth plaster mortar. To classify the energy balance and environmental balance of earth plaster mortars, the total primary energy input (PET) and the greenhouse effect (CO_2 eq./GWP) of both production processes were compared with the corresponding values of common mineral plaster mortars and with generic values for earth plaster mortars published in the official database of the Federal Building Institute (ÖKOBAUDAT). Depending on the manufacturing process, the total energy input PET of the earth plaster mortars investigated is up to an order of magnitude less than that of other mineral plaster mortars and two orders of magnitude less in terms of its Global Warming Potential GWP.

The completed project addressed scenarios for "dry" and "wet" approaches to the reuse of (cleanly separable) recovered plaster mortar for the first time. For each processing scenario, ecological savings potentials were calculated. The practical feasibility of these scenarios was successfully demonstrated in a building materials laboratory situation as part of an accompanying diploma thesis at the FH Potsdam. In April 2020, work began on the continuation of the project as part the DVL "UPD Lehm.2" project [3a], again funded by the DBU.

Table 7 Environmental impact indicators for reprocessing (C3) and recycling (D) [1]

			Scenarios			
			Wet process		**Dry process**	
No.	**Indicator** (annual mean, ref. unit 1 kg mass)	**Unit**	**Module C3**	**Module D**	**Module C3**	**Module D**
1	GWP: Global Warming Potential	kg CO_2 eq.	2.89E-03	-2.19E-03	1.63E-03	-2.37E-03
2	ODP: Depletion pot. of stratospheric ozone layer	kg R11 eq.	5.39E-12	-4.88E-10	6.83E-12	-4.95E-10
3	POCP: Formation pot. of tropospheric ozone	kg Ethylene eq.	2.44E-06	-2.44E-06	1.76E-07	-2.80E-06
4	AP: Acidification potential of land and water	kg SO_2 eq.	7.21E-06	-1.48E-05	2.49E-06	-1.67E-05
5	EP: Eutrophication potential	kg PO_4 eq.	1.34E-06	-4.53E-06	4.04E-07	-4.76E-06
6	ADPE: Abiotic res. depletion pot. for elements	kg Sb eq.	1.26E-06	-1.49E-08	1.05E-06	-1.08E-08
7	ADPF: Abiotic res. depletion pot. of fossil fuels	MJ	3.43E-02	-3.11E-02	1.64E-02	-3.37E-02

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