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Earthen building materials as an opportunity to reduce mineral construction and demolition waste (CDW)

The construction sector is one of the most resource-intensive sectors in Germany and is responsible for 51% of CO_2 emissions. Annually, around 517 million tons of mineral raw materials are required for the construction of buildings [1]. At the same time, around 228 million tons of construction and demolition waste were generated in 2018, which accounts for 54.7% of the total waste volume [2].

The new waste hierarchy outlined in the KrWG since 2012 determines reuse and recycling as the most important instruments after waste prevention [3]. In Germany, the reuse or further use of parts of buildings or building components takes place only to a very small extent and occurs mostly in construction activities in the field of cultural heritage or smaller private building projects. On the other hand, the recycling rates for CDW – Construction and Demolition Waste – have increased significantly over the past 20 years, especially for mineral waste. Nevertheless, the majority of recycled aggregates are used in largely unregulated technical applications, e.g. as backfill material in earthworks, civil engineering and road construction. This classical downcycling means that valuable resources for technically and economically high-quality uses are lost.

A large part of the mineral waste continues to be landfilled despite changes in legislation regarding the establishment of a circular economy. Waste figures show that mineral construction waste with 214.6 million tons (2016) represents the largest material flow within the national waste balance, of which 125.2 million tons are soil and stones and 58.5 million building rubble [4]. For the fine fraction (grain size < 2 mm) in particular, which accounts for up to 5 million tons of waste, suitable applications are still currently lacking, as they have not yet been approved for recycled concrete as detailed in DIN EN 206-1 and DIN 1045-2. These material flows are mostly diverted to landfill and only partially used as subsoil in road and landfill construction. It is expected that the envisaged 'Umbrella Ordinance' with revisions and updates to federal landfill and commercial waste legislation [5] will increase this proportion further.

The use of these grain sizes, which make up between 5% and 70% (by volume) of earth building materials, depending on raw materials and products, is not permitted in the current standard for earth building materials (DIN 18945 to 18948). According to DIN EN 12620, only natural aggregates and according to DIN EN 13055-1 only brick powder made from mortar-free bricks and expanded perlite etc. are permitted, whereas for binders only soil from natural sources are permitted.

To enable the use of recycled construction and demolition waste for earth building materials in standardisation,

- the technical feasibility,
- quality requirements for substitute building materials (e.g. limit values for possible pollutants in relation to health and environmental compatibility – groundwater/soil – as well as dangerous substances)
- permissible proportions of recycled materials

have to be determined.

As part of the EU-funded research project **RE**^{4} – **RE**use and **RE**cycling of CDW materials and structures in energy efficient p**RE**fabricated elements for building **RE**furbishment and construction –, concepts were developed to minimise various waste streams. In addition, strategies were developed to demonstrate how these materials can be returned to and retained in the building cycle in the long term. This study focuses on the development of earth building materials based on mineral waste. The main goal was to develop applications for the fine and ultra-fine fraction, as these are difficult or impossible to use for the production of recycled concrete. Material developments were carried out for earth plaster and mortar as well as rammed earth.

In addition, opportunities of circular construction were examined in an experimental study and the dismantling and reuse potential of different earth building materials (earth plaster and mortar, earth adhesive, earth dry lining board) and supplementary products (reinforcement fabric, screws) are shown using the example of an internal wall system. At the end of its use phase (approx. 1 year), the wall system, located in an office extension, was dismantled and scheduled for rebuilding at a new location. The individual products were rated according to their potential for direct reuse and recycling. An accompanying life cycle analysis (LCA) provided valuable results with regard to the sustainability values of earth building materials.

Materials and testing methods

Provision of material

Earth building materials have outstanding potential in terms of their reusability. However, when it comes to the material development of earth building materials based on construction and demolition waste, there have as yet been few investigations into the technical and economic feasibility. Besides the fact that earth construction has only a small market share, it can be assumed that, as with other building materials, the simple and to date inexpensive access to primary raw materials, the varying composition and quality of CDW and related issues such as the presence of unwanted pollutants are the main reasons.

This question was investigated as part of the RE[4] project. The project focusses on recycled aggregates < 2 mm, as well as residues from the washing processes of the CWD, since these are not approved for use in the production of recycled concrete and are almost entirely disposed of. At this point, it is important to note that the question of possible pollutant contents was not dealt with here, as the investigation only represented a partial aspect of the overall project. CDW from different regions of Europe – Northern (NE) and Southern Europe (SE) – were used to reflect the topic of changing material qualities and construction methods.

The incoming batches were provided by one of the project partners (CDE) in various sorting qualities as well as purchased. Initial tests were carried out with recycled material that had just gone through a simple sorting process. Visual inspections confirmed this and showed that these batches contained a large number of impurities such as glass, bricks and tiles. Other mixes were manufactured, based on an improved sorting of the base material. Table 1 provides an overview of the materials used for the development of building materials, which consisted of different CDW's and one primary raw material (clayey soil). The clayey soil, < 0.5 mm, dry, was purchased in Berlin and was used to supplement the silt and clay press cake if required. It should be noted that the recycled grain sizes 0-2 mm also partially contained silt and clay due to the sorting methods.

Methodology

Two different strategies were used for the material development. For earth plaster and mortar, a ready-made binding agent was used, which was tested by

Table 1. Recycled aggregates and primary raw materials and their intended use.

Construction and demolition waste	Primary raw materials	Grain sizes	Origin Use	Application
Silt and clay press cake		< 0.063 mm	SE/NE	binder for rammed earth
Sand		0 – 2 mm	SE/NE/Berlin	aggregate for earth plaster, mortar and rammed earth
Fine gravel		2 – 8 mm	SE/NE	aggregate for rammed earth
Medium gravel		8 – 16 mm	SE/NE	aggregate for rammed earth
	Clayey soil	< 0.5 mm	Germany	binder for earth plaster, mortar and rammed earth

the manufacturer with regard to its binding forces in accordance with the Lehmbau Regeln [6]. This approach made it possible to focus on maximising the proportion of recycled material for the respective mixture. In order to increase the efficiency of the material development, the aim was to develop a mixture applicable as earth plaster and mortar. Since some batches demonstrated a suitable grain size distribution necessary for the development of rammed earth, the strategy for this material development was adapted. In order to also produce the binder from a maximum amount of recycled material, the silt and clay press cake was used entirely, and clayey soil was only added if required. This strategy is possible because the setting of a rammed earth mixture is less complex, and the effect of the binding agent is less pronounced.

Adhesive force

In a first step, the general suitability of the silt and clay press cake for the development of a binding agent was examined by means of a so called 'Achterlingsprüfung' (a test for determining binding force) according to the *Lehmbau Regeln* [6]. The material was placed in an 8-shaped test mould and the binding force was determined as the mean value of three tensile tests.

Carbonate content

To prove the general suitability for use as a building material, the lime content of the silt and clay press cake was determined according to the Lehmbau Regeln and to DIN EN ISO 14688 as a semi-quantitative determination of the lime content (natural lime or added lime as a binding agent) [6] [7]. Diluted hydrochloric acid was sprinkled onto the crushed sample material and the effervescence from carbon dioxide as a product of the reaction between acid and carbonate was assessed.

Sieving curve

To characterize the CDW aggregates for the development of earth plaster and mortar, the particle size distribution of the sand fraction (0-2 mm) was determined and compared with one another. The final sieving curves provide an indication of the mechanical properties and the influence of the aggregates on the strength properties of the developed earth building materials.

Test methods for earth plaster

The developed earth plasters were tested in accordance with DIN 18947 (mandatory and voluntary tests), which sets out the requirements for earth plasters for use in indoor and weather-protected outdoor areas [8]. A strength class of S II was defined as the goal to enable unrestricted use of the material.

Test methods for earth mortar

The developed mortars were tested in accordance with DIN 18946 (mandatory and voluntary tests), which sets out the requirements for earth mortars for use in indoor and outdoor areas protected from the weather [9]. Tests for shear strength were not part of the project.

Test methods for rammed earth

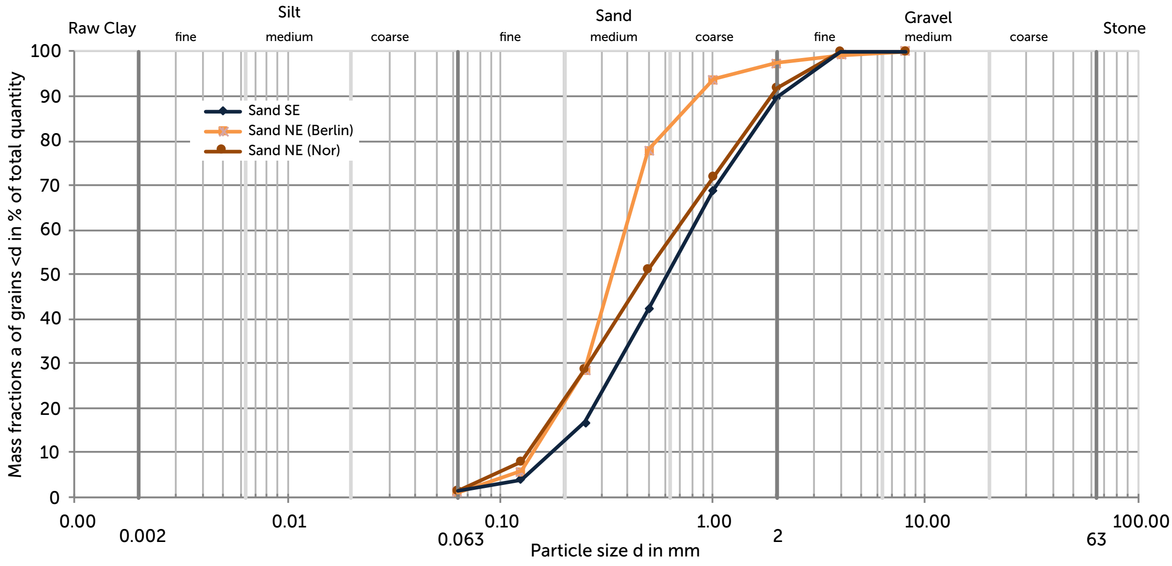
The developed rammed earth mixtures were tested with respect to the linear drying shrinkage. The bulk density was also determined but testing of the compressive strength was not carried out as part of the project. As the building material developed is intended for non-load-bearing applications, this test is not mandatory.

Dismantling potential of an earth dry wall

In order to evaluate the potential of the developed but also other earth building materials in relation to circular construction, the ability to dismantle and reuse drywall systems was examined in an experimental study. For this purpose, a 35 m^2 interior wall system was dismantled that had served as a partition wall in an office extension. The wall is a non-load-bearing wooden stud construction lined with earth dry lining boards and plastered with a 2-coat earth plaster system. The earth plaster system was removed and broken down in a 'wet process'.

Life cycle assessment

The life cycle assessment was carried out for two drywall systems. The first wall construction consisted of natural building materials (wooden studs, wood fibre insulation, earth dry lining board, earth plaster system, silicate paint) and the second of conventional building materials (metal studs, mineral wool, plasterboard, dispersion paint). The LCA balance was prepared using Ökobaudat [10]. Based on the results of the experimental study of the dismantling potential of earth dry walls, it was assumed that the system can be dismantled and rebuilt twice within the study period of 50 years.



01 Comparison of the particle size distribution for the 0-2 mm fraction

Results

Adhesive force

The 8-shaped test specimens showed an average binding force of 157 g/m², which means that the press cake can be classified as 'almost fat' and is therefore suitable for the production of earth building materials.

Carbonate content

The test revealed a strong, long-lasting effervescence, indicating an increased level of lime content at various particle sizes. However, the material was suitable for the development of earth building materials.

Sieving curve

The mineral CDW from NE and SE contained a small proportion of oversize grain > 4 mm. Although the grain size distributions of the different CDW's are similar, as shown by the course of the grain distribution curves, the greatest difference lies in the proportion of grain sizes > 0.25 mm, which was around 8% higher for deliveries from NE than for deliveries from SE. The oversize fraction > 4 mm of the 'Berlin sand' was significantly higher, while the content of the grain fractions 2, 1 and 0.5 mm was significantly lower.

The fraction of the fine fraction < 0.063 mm was very low for all recycled aggregates and accounts for only 1.4% of the material. Figure 1 provides an overview of the most representative sieving curves for CDW material from the various sources.

Test methods for earth plaster

For material development, different mixing ratios of CDW aggregates and binders from different sources (SE, NE and Berlin) were tested. In addition, the workability was evaluated during the production of

Table 2: Results of mandatory and voluntary tests according to [8], [9] with optimised mixture (initial test).

Property	Unit	Mixture SE-2	Required* / target value plaster	mortar	Result	Comment
Drying shrinkage	%	1.9	< 2*	< 2.5*	ok	little contingency
Bulk density	kg/dm³	1.67	> 1.41*	> 1.41*	ok	
Bending tensile strength *1	N/mm²	1.0	> 0.7*	/	ok	
Compressive strength *1	N/mm²	2.7	> 1.5*	> 2.0*	ok	
Adhesive strength *1	N/mm²	0.12	> 0.10	/	ok	
Abrasion *1	g	0.1	< 0.7	/	ok	
Water vapour adsorption test (12h)	g/m²	94	60	/	WS III	excellent result

*1 *Strength class S II*

the mortar mixes and the test specimens. The most promising mixture, which fulfilled all requirements of the preliminary tests according to [6], was subject to a complete test campaign for earth plaster and mortar [8], [9]. This mixture contained two parts (by volume) of the 0-2 mm recycled material and one part (by volume) of the clayey soil and thus in total 67% of CDW content (by volume). Repeat tests were carried out in order to assess the reproducibility of the results. Table 2 documents the test results of the mandatory and voluntary test for the optimised mixture according to [8], [9] and shows that all requirements were met during the initial test.

The drying shrinkage demonstrates little contingency and the required value was not achieved in the repeat tests. However, this property could successfully be adjusted by adding fibres or further optimisation of the mixture. Both measures would also improve the flexural strength of the material mixture, which could not be repeated either. Although suitable fibres from construction waste were not provided within the project, the aim is to develop them from waste wood. The compressive strength was achieved in all tests with a clear excess of the limit value. For the adhesive tensile strength test, there was an unusually high standard deviation. The results of the voluntary water vapor sorption test achieved above-average results of 94 g/m^2, which exceeds values of market products by approx. 30-50%.

Test method for earth mortar

Since the aim was to develop a mixture suitable for use both as plaster and mortar, the majority of the test results could be used for the assessment of both applications. The corresponding test results are shown in Table 2. The results of all initial tests carried out were above the target values. The shear strength test was not carried out as part of the project.

Test methods for rammed earth

The bulk density of the mixtures resulted in a value of > 1.41 kg/dm^3. The linear drying shrinkage reached a value of 0.25%, which is below the threshold value of 0.5% for monolithic visible components and well below the value of 2% for monolithic components.

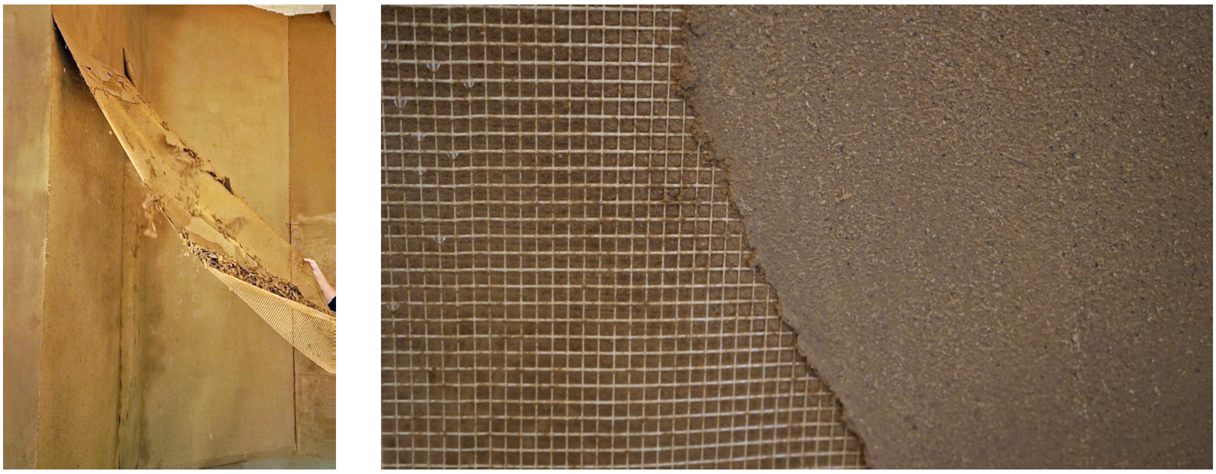
Dismantling potential of an earth dry wall

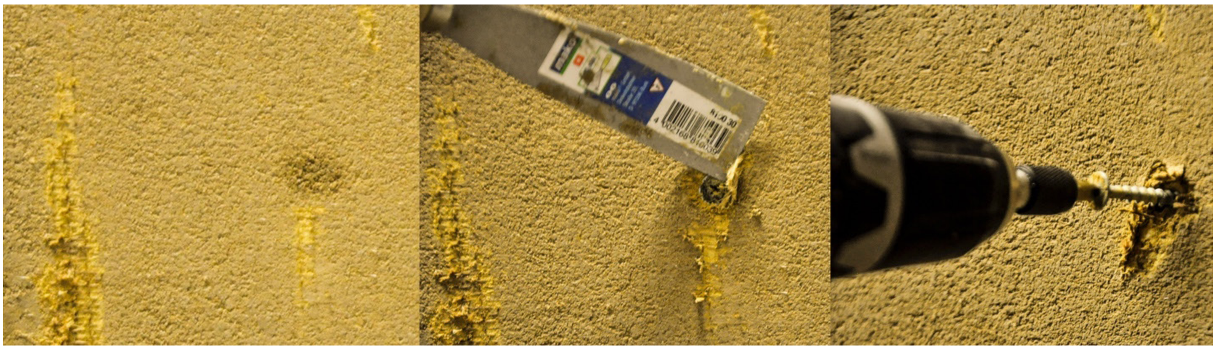
The earth dry wall could be dismantled completely and almost in a non-destructively manner. The wetting of the earth plaster turned out to be very effective, as the inserted fabric could be used to separate the plaster from the earth adhesive almost completely as single-origin (Figure 2–3). Since two different fabrics (fibreglass and jute) were installed, the dismantling process showed that only the fibreglass fabric was suitable for 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 could be reused. The reconstruction of the wall system is still pending due to covid-19. Figure 4 shows the sequence of the dismantling process of earth dry lining boards.

Life cycle assessment

Seven impact indicators were examined in the life cycle assessment. The earth dry wall showed signifi-

02-03 Dismantling of the earth plaster layer





04 Sequence of the dismantling process of earth dry lining boards

cantly better results than the conventional internal wall system for six indicators. Only for the ozone depletion potential (ODP) was the value for the earth dry wall significantly worse. Figure 5 shows the indicators examined and the results of the assessment.

Discussion

Adhesive force and determination of the carbonate content

All screening tests, including those not published in this study (e.g. moisture content at delivery, olfactory test), showed promising results. The silt and clay press cake was generally suitable for the development of earth building materials, provided that:

- the content of organic substances is very low in order to avoid the formation of mould;
- the material is sufficiently dry to allow even mixing with other aggregates;
- appropriate aggregates are added to lean down the material to prevent cracking

Sieving curve

Although the incoming CDW material (0-2 mm fraction) had a different grain size distribution, earth building materials that met the requirements could be produced from all batches. The effect of the different grain distributions can be considered as negligible for the CDW examined.

Test methods for earth plaster

The investigations carried out have shown that it is technically possible to manufacture an earth plaster based on recycled aggregates instead of sand from primary raw materials and that this mixture can also be used as earth mortar. However, a fixed mixing ratio that reliably meets the requirements of the German DIN 18946 and DIN 18947 standards has not yet been determined. The proven mixing ratio of two parts CDW aggregate (by volume) and one part clayey soil (by volume) can be used as the starting point for every new development. The ratio of CDW content within the developed mixture was 67%.

Test methods for earth mortar

Although the shear strength test was not carried out, it can be confirmed that the best mixture meets all the remaining requirements of DIN 18946.

Test method for rammed earth

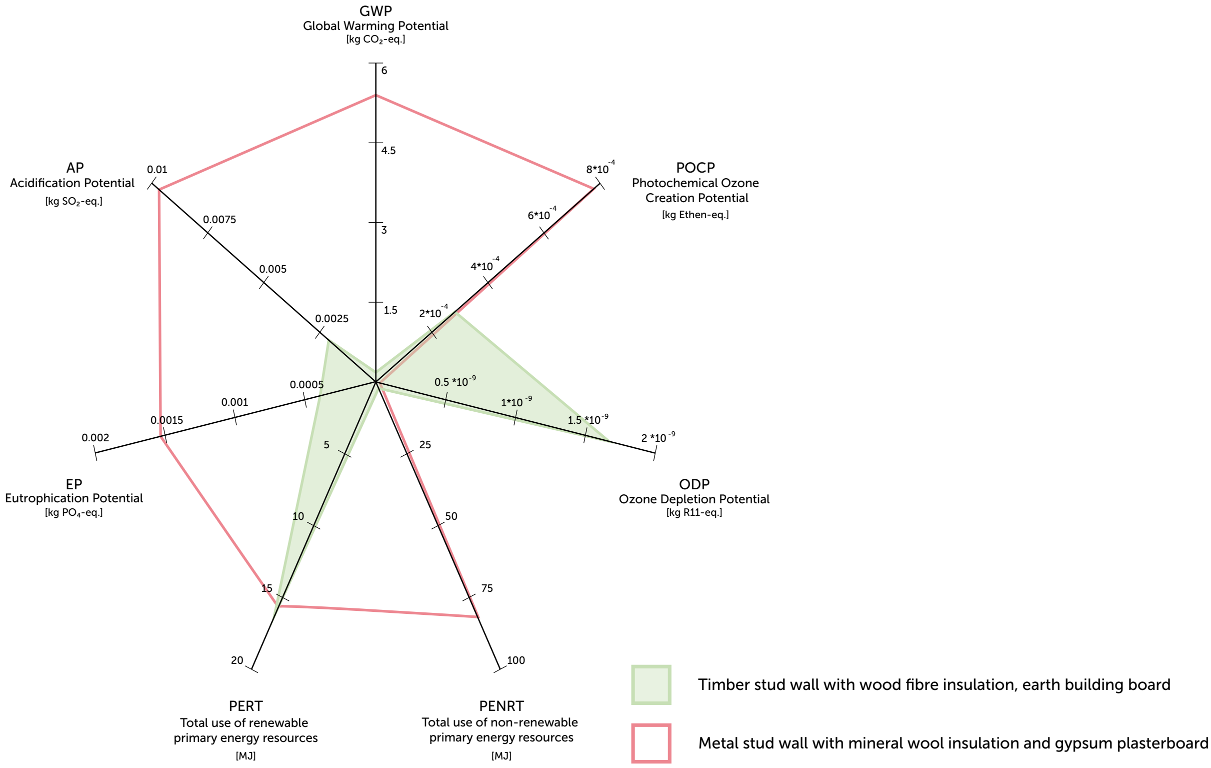
The material mixture for rammed earth meets all requirements for non-load-bearing applications and demonstrates with 87% the highest proportion of recycled material. Further investigations should make it possible to additionally substitute the binder with CDW material. Compressive strength tests are still pending for load-bearing applications.

Dismantling potential of an earth dry wall

The experimental study demonstrated the very high dismantling potential of earth dry walls. A prerequisite for this is the use of a selective dismantling method. The amount of waste can be reduced to almost zero, as even broken panels and non-reusable screws can be recycled (Figure 6). The recycling potential of the jute fabric needs further investigation.

Life cycle assessment

The outstanding results of the life cycle assessment underline the future potential of earth building materials for circular construction 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.



05 Life cycle assessment of two internal wall systems

Conclusion and outlook

Overall, it can be stated that all material developments presented in this study required very little effort and that the respective requirements were met without major adjustments to the mixtures. Although the silt and clay press cake had to be watered and processed with hand tools, the sand fraction could be used without further processing such as sifting. Even if the CDW materials exhibited a certain heterogeneity, the typical quality and average composition were comparable regardless of the source.

For time reasons, the silt and clay press cake was only used for rammed earth mixes. Further investigations and tests would be necessary in order to assess whether the binder can be fully replaced by the silt and clay press cake. This would require that the material is free from pollutants and humus. In addition, each batch of the silt and clay press cake would have to be checked for suitability as a binding agent, as individual batches may not be suitable because they contain too little or too much binding content, necessitating corresponding adjustments.

A range of suitable mixing ratios can only be roughly defined. If earth building materials are to be made entirely of CDW material, the mixing ratios must be individually determined for the available materials.

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.

Acknowledgements

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06 Amount of waste from the dismantling process of 35 m^2 of earth dry wall

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