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State of the Art and Potentials of Additive Manufactured Earth (AME)

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Abstract

Additive production techniques such as 3D printing and robotics enable new production methods and possible uses for earth, as one of the most ancient building materials in the building industry. This study examines the potential of different building elements and components and their possible combinations made of or containing earthen building products. In addition to the 3D printing of lightweight, highly insulating external and heavy internal wall elements and load-bearing rammed earth walls for use as inner and outside walls are compared. Furthermore, the activation of the walls with water-based heating and cooling elements is taken into consideration. In particular, the sensitivity of earth to humidity and water has a positive effect on all life cycle phases from production through operation as a low-tech building to the end of use, i.e. the reuse as well as the possible return to natural cycles. The focus of the study is to assess the building material earth in light of modern production methodologies, the impact on indoor comfort and indoor air quality as well its life cycle assessment.

Keywords
Earth construction, circularity, indoor environmental quality, user satisfaction, user health, additive manufacturing

1 INTRODUCTION

As an estimation, 30% of all houses worldwide are built from earth (Keefe, 2012). Besides regions in which earth as a building material is the only available resource, in Europe, the number of buildings made from earth is increasing slowly. This essentially does not result from earth as the only available resource but from demands of sustainable, healthy and comfortable living (Minke, 2017). Not only from an indoor environmental quality (IEQ) point of view but also from technical aspects, earth has a high potential of minimizing the energy demand which is used for the operation of buildings. Buildings from earth not only positively affect the human well-being inside the building but also have a positive impact on the outdoors, contributing to the resilience of cities against heat stress (Santamouris, 2013). This is already well understood in warmer climates (e.g. street canyons in arid climate), but considering global warming, the consideration makes increasing sense in colder climates and dense cities.

Earth as a building material still has a low market share in European regions which could be caused by lost knowledge from construction companies that are not familiar with the building techniques (Minke, 2017). Furthermore, buildings from earth can only be cost-effective when the building process is (semi) automated (Kloft et al., 2019). The structure of building elements from earth are usually rammed earth, blocks, dry boards or plasters, whereas supportive additive manufacturing processes could enhance not only the production process itself but also indoor environmental qualities.

Historically, earth is used with different techniques in form of earth blocks and rammed earth as a solid construction or as fillings in wattle-and-daub buildings. In different cultures, earth is used in a variety of techniques and designs as a cladding material, mostly as plaster but also as dry earth boards. Due to its climate-controlling and ecological potential, earth is gaining increasing attention as a building material. In Germany, the standardization of earth building products has been progressed intensively in recent years. Standards for earth blocks (DIN 18945), earth mortar (DIN 18946), earth plaster (DIN 18947) and earth dry boards (DIN 18948) have been introduced.

Due to the small market, the use of earth is still very artisan. New manufacturing technologies such as 3D printing and robotics will unlock the potential for optimizing the use of earth in the construction industry and are expected to contribute to the further spread of earth buildings.

In order to develop the full potential of products from additive manufactured earth, the advantages of earth construction need to be maintained. Therefore, the objective of this article is a multi-dimensional discussion of the main relevant capacities, which are here considered as indoor environmental quality, user satisfaction, and the circularity against the background of evolving technologies to assess the potential of the new technologies.

2 METHODOLOGY

In this article, the potentials of earth products are described and classified from different perspectives. Firstly, the technology with the latest developments in additive manufactured earth products is introduced. Secondly, the state of the art of the most relevant capacities (indoor environmental quality, user satisfaction and circularity) is summarized. In the discussion, the status quo is outlined, and the potential of additive manufactured earth products to improve the market share and the application within moderate climate zones is discussed. Subsequently, the assessments are overlaid with each other to reflect the status quo of AM earth products, demonstrating the potentials for the application in the building industry.

While the potential of additive manufactured earth products is discussed based on the technology and the relevant capacities on an abstract level, the findings presented below are based on a literature review, experiences from practice and from small size produced prototypes by the authors. The section on user satisfaction is based on a literature search in web of science and sciencedirect, using search terms including "rammed earth", "earth building" or "earth plaster" in combination with "comfort", "well-being", and others, which revealed 37 journal articles of which only 11 were suitable for this article after reviewing their content in detail.

3 ADDITIVE MANUFACTURING TECHNOLOGIES

In general, AM technologies will be distinguished by the nature of the raw material and the methods used to produce the different layers of the structure, as well as by the joining phase of the layer differences. Before the material is processed, there is a digital planning process in which the object to be created is digitally created in three dimensions and then broken down into layers so that the corresponding additive manufacturing process can process it.

The usual technologies currently in use are Selective Laser Melting (SLM), Direct Metal Laser Sintering (DMLS) and Selective Laser Sintering (SLS), all three processes in which a thin layer of powder is melted using an energy source at the points where volume is to be created. In a next layer, the same process is repeated in a higher layer until a corresponding volume is created. The Fused Deposition Modelling (FDM) and Fused Filament Fabrication (FFF) processes work differently in principle: the material is extruded from a nozzle, and individual layers are created by controlling the nozzle or the carrier platform, which then produce the desired volume according to the digital control (Lim et al.; Knaack et al. 2010; Knaack et al. 2016). Other technologies like stereo-lithography (SLA) or Laminated Object Manufacturing (LOM) are alternative methods of additive manufacturing, but technologies do not currently appear to make much sense for use in earth.

Earth consists of sand, silt and clay. Depending on the corn size distribution, it can be used for different purposes in construction. By optimizing the mineral composition and adding natural fibres, for example, the properties can be optimized according to its purpose. Additive production techniques such as 3D printing and robotics enable new production methods and possible uses for earth, as one of the most ancient building materials in the building industry. This chapter introduces the most relevant techniques.

3.1 AUTOMATED RAMMED EARTH

Based on one of the traditional production methods for components made of earth, the rammed earth technique, automated rammed earth technologies have been developed. In a first step, the material is penetrated by means of automation and then automatically compacted. In this process, components can be produced both on-site and as finished parts that are subsequently transported (Heringer, Blair Howe, Rausch; Djahanschah, Auer, Kaufmann;). This process has already been tested several times and is currently being used in the construction industry for limited and individual projects. In a further development step, the automated rammed earth technologies can be developed towards an automated control of the formwork, which offers the principle advantage of free control of the form. This process has so far only been investigated experimentally (Kloft et al.).

3.2 DIGITALLY CONTROLLED BUILDING ELEMENT EXTRUSION

Following the system of the FDM Technology there is the possibility to create large-sized building elements and structures on-site by means of extrusion. In this case, a cord of earth is placed on the underlying cord by means of extrusion and thus creates the volume. The process allows the creation of large volumes relatively quickly and is currently being investigated experimentally at various institutes in the USA and Europe. Semi-industrial production is active in Italy (WASP).

3.3 DIGITALLY CONTROLLED COMPONENT EXTRUSION

Also based on the extrusion, small components as parts of building elements can be purchased for the first time, which are developed for complex geometric situations or additional functions and can then be produced by means of digitally controlled extrusion and transported after drying. The principal technology of digitally controlling the extrusion of earth is being investigated by various institutes in Spain, Hong Kong, the Netherlands and Germany, but up to now, it has always been followed by a firing process to produce a brick as a special shape from the component (Knaack et al., 2010; Knaack et al., 2016). Next to the individualized volume itself, the surface of the object can be designed to improve its performance.

4 INDOOR COMFORT

Certainly, the best-understood fact is that earth buildings have a high thermal capacity so that heat can be buffered to times with lower temperatures and thereby shifting temperature peaks and reducing active cooling to a minimum. Due to the fact that the heat transfer is driven by the temperature difference between surface and adjacent air one can speak of a self-regulating effect since the heat flow from or into a building element depends on the temperature difference (BINE, 2007). Combined with materials having lower densities, an insulating building material can be produced, making earth as a building material likewise interesting for colder climates using porous mineral aggregates (e.g. foamed glass). If the wall structure is built from 100% reusable materials, a minimum of embodied energy content is achieved if structural or insulating elements are built from wood or straw.

In addition to other mineral materials earth is porous and has the capability to buffer also large amounts of humidity from the air. This hygroscopic behaviour can be described as the sorption of humidity. The measurement procedures of sorption processes are standardized. During a constant air temperature of 23°C and a rise in relative humidity from 50 to 80% is induced while the control volume is weighted continuously to identify the absorption of water during at least 12 hours (DIN 18945-18948). Under laboratory conditions, a wall made from earth which is exposed from both sides to a rise in relative humidity the ability to absorb water from the air is described as nine times higher compared to a wall made from concrete (Minke, 2017). Considering real-life operating conditions, the ability of humidity sorption from the air into earth dry boards is 3-5 times higher compared to plasterboards made of gypsum (Klinge, 2016). Here 100 g/m^2 of humidity is absorbed by the earthen product with a thickness of 20 mm after 12 hours compared to 20 g/m^2 absorption by the gypsum board. It can reasonably be concluded that the self-regulating effect of the air temperature is also applicable to self-regulation in relative humidity (Lan et al. 2017).

Considering the local climate during the design process, the hygrothermal properties (thermal capacity, insulation, humidity buffering) of earth provides the potential to reduce the demand of technical equipment (Djahanschah,et al., 2020). In the example the risk of mould (in bathrooms) due to peak-loads of moist can be compensated by the ability to absorb humidity quickly (McGregor et al., 2016). Hence, ventilation rates of peak loads can be reduced. Two residential buildings, which are operated within German climate conditions where one is built from conventional materials and the other is built from natural materials shows a significant difference in humidity levels (Klinge, 2016). The building which is made from natural materials shows that humidity levels range almost between 50% - 60% which is a spectrum providing healthy conditions whereat buildings made of conventional materials show lower rates in relative humidity with higher alterations. To achieve those healthy conditions, it can be discussed that active humidification and hence an air conditioning system is obsolete if the building is designed with proper materials.

On the basis of AM technologies and automated construction techniques, the surface texture itself can be optimized. This could be achieved with an increase in surface area through a roughened texture of the surface by for example digitally controlled component extrusion. This could result in a higher transfer of humidity and heat flow between the air and the building element. As another potential, the inner characteristics of building elements from earth could be adjusted during the additive manufacturing process so that modified thermal masses and insulating properties are made from one homogeneous material.

Furthermore, the material can be equipped with functions by the material itself (e.g. openings for ventilation, cavities) or with technology. Chilled walls with earth as a material base that could be plastered cooling systems as well as prefabricated earthen dry wall systems with embedded cooling system have the benefit of reducing the risk of condensation leading to the possibility of lower supply temperatures; hence, higher cooling rates are possible. The fact that peaks of the relative humidity can be buffered and flattened the opposite is valid for cases in which dehumidification is necessary. With a chilled ceiling or a thermo-activated building system, dehumidification is thinkable.

5 USER SATISFACTION AND HEALTH

From the viewpoint of human comfort, satisfaction and health, lower indoor temperatures and humidity levels, due to above-described characteristics of earth, reduce the thermal strain and increase the level of satisfaction under warm summer conditions (Parsons, 2014). In addition, respiratory health effects during wintertime are caused by rather low relative humidity levels (Mäkinen et al., 2009), potentially reduced with earth materials regulating humidity levels.

However, studies looking specifically at the effect of earth materials on user satisfaction and health are scarce. Furthermore, when considering rigorous scientific methods (i.e., meaningful sample sizes and controlled experiments), nearly all of these studies cannot draw conclusions on systematic cause-effect relations. At the same time, their findings are useful for formulating research questions and hypothesis for future research.

A first group of studies looks at direct effects. Li et al. (2013) compared traditional Chinese Tulou buildings made of rammed earth in a wooden framework with close by “normal rural buildings”. They obtained 139 questionnaires from six Tulou buildings and 97 responses from an undefined number of normal buildings and performed additional IEQ measurements. They observed higher thermal satisfaction with the Chinese Tulou buildings compared to normal rural buildings, but no differences in the perception of the luminous and indoor air quality environment. However, their study cannot reveal whether the observed differences are due to different building materials or the differences in architecture and style of buildings. Fernandes et al. (2019) base their conclusion on a single rammed earth building in Portugal with measurements and subjective votes of five respondents. Thermal performance was satisfactory during summer, but heating was required in winter. Beckett et al. (2017) compared one building with traditional solid rammed earth walls with one other building with rammed earth walls including an insulating polystyrene core in Australia. Both buildings led to high thermal satisfaction in winter and summer, with only short periods with heating demand in winter. Noteworthy, occupants’ ratings were more positive than predicted by calculated satisfaction indices. These examples confirm the focus on thermal aspects when dealing with earthen constructions, while additional direct effects due to the application of above-described technologies can be envisioned. These effects include the potential of earth plaster optimizing acoustic properties while keeping thermal mass activated; increased satisfaction with the indoor air quality due to lower temperatures and the known effect of cooler air perceived as more fresh (Fang et al., 1998); and an improved visual environment through enhanced visual properties of the surface minimizing glare.

Compared to such direct effects, indirect effects mentioned in the literature are even more difficult to be assigned solely to the application of earth as building material. Deuble and de Dear (2012) found that occupants in green buildings tended to forgive their buildings IEQ conditions outside classical comfort ranges more likely than occupants in conventional buildings. Again, the evidence is based on case studies partly contradictory and not systematically assessed. For example, Taylor et al. (2008) found no difference in occupants perception with respect to thermal, visual, and acoustic aspects comparing one rammed earth building with one other conventional building. Supporting the existence of such an effect, Sant'Anna et al. (2018), Leaman and Bordass (2007) and others found strong positive effects of green buildings on user satisfaction compared to conventional buildings. Due to small sample sizes and the large variety in human perception and preferences, the debate is still ongoing and further well-designed research required.

In this context, the notion and importance of perceived control is a crucial aspect to be considered. Evidence from studies not addressing earth buildings suggest positive effects of perceived control on user satisfaction (e.g. Brager et al. 2004, Schweiker et al. 2016). Keeping buildings simple will help their users understanding their behaviour. At the same time, a buildings' capability of self-regulation should not reduce control opportunities for individual comfort.

A final note shall be given on the effect of building with earth and "feeling earth" on human health. Based on an experimental study with 36 Chinese adult participants, Wong & Au (2019) concluded that participants who created earth work using their bare hands improved significantly in positive mood and well-being immediately after the session, compared to those wearing gloves. Nan and Ho (2017) reported a positive effect of earth art therapy compared to visual art therapy on emotion regulation and other aspects of mental health in adults with depression based on an experimental study with 106 participants. These studies reveal interesting potential side-effects of building with earth.

6 CIRCULARITY

Circularity is a strategy that aims in balancing human needs for resources and environmental concerns by designing circular flows. In the context of the building industry, different levels can be considered like the flow of finances or the flow of information. The environmental impact is related to the material or resource flow which is considered in the following.

Resources in the building context are used to operate the building as gas or oil for heating, cooling and electricity. Furthermore, resources are used to form the building substance - its construction materials. Due to high insulating building envelopes and efficient technology, which provide growing shares of renewable energy, the relevance for resources in the building context is growing.

In order to evaluate the extent of circularity of construction materials, two categories are distinguished: 1) the material which is or is becoming part of the construction (input) and 2) its after-use potential (or potential output). Different methods by different stakeholders like the Dutch platform CB23 (CB'23, 2019; Foundation; & Design, 2015), institutions like most relevant the Ellen Macarther Foundation, universities e.g. RWTH Aachen (Hildebrand, Schwan, Vollpracht, Brell-Cokcan,

& Zabek, 2018) or architects and engineers (Hillebrandt, Riegler-Floors, Rosen, & Seggewies, 2018) are available with the attempt to evaluate design decisions and quantify circularity.

In order to discuss the circularity of earth products and additive manufactured earth products the two categories input and potential output are used.

Input. Earth products are most commonly used in near proximity and often manually processed. Hence, only little energy and emissions are linked to the transport and the processing of earth products. This results in low values for primary energy not renewable ranging from 0,07 to 1, 05 MJ/kg and for global warming potential 0,004 to 0,06 kg CO2eq/kg (Schröder, 2019). In comparison with other building materials, the thickness needs to be considered. While solid construction from bricks, limestone or concrete with insulation typically result in thicknesses from 25-40 cm, a wall with the same functionality from earth will need 40-70 cm. Even with the increased material amount, the earth wall, if produced with low-tech measures, will result in significantly lower values.

For additive manufactured earth products, the machine work is highly relevant. Studies on this aspect are not available. Environmental data on automated processes were investigated in a study on deconstruction of façades (Hildebrand, Schwan, Vollpracht, Brell-Cokcan, & Zabek, 2018). The processes are comparable to producing rammed earth; the findings show that the effort for cutting and lifting are as energy-intensive as processing the construction again. Furthermore, a wide variety of machine efficiency can be found; older machines use more energy. When renewable energy is used, the environmental impact can be reduced significantly. In respect of the printing process, different results can be expected as no lifting of bigger pieces is involved. Additionally, only necessary material is placed, which can potentially reduce the overall resource spent on a construction.

The deconstruction of earth products is manually and mechanically doable. The material can be processed (in order to provide homogeneous material) and used in a different construction like it was done with the earliest earth products, documented for 8000 B.C. in Afrasiab (today Samarkand), which were isolated from a building context, processed and used as a recycled building product in a new building. When grade purity is provided, the material keeps its recyclability endlessly.

For additive manufactured earth products, especially for printed construction, the ingredients can vary. Additives and aggregates are used in order to impact the viscosity during the printing process and limit the shrinkage while drying. Fibres from vegetables, animals or minerals can be added to support the material strength. Additives can be hexametaphosphate (HMP), ash or enzymes. Experiments from IACC document the interdependencies between the material properties and the construction geometry in which the printing pattern follows the material strength and provides an original shape. Schröder (2019) distinguishes additives that impact the chemical properties of earth products and additives that do not. While the first group has no effect on the circularity of the material, the latter has; since the additives cannot be sorted out, the product is impure and limited in its application. Recycling is no longer possible. Examples here for are cement, chalk or fly ash.

7 SYNOPSIS OF POTENTIALS

Even if earthen construction is one of the oldest construction techniques known to mankind, the scientifically proven knowledge of this building technique is limited. Although the hygric capabilities, i.e. moist sorption and desorption of the material, can be demonstrated using the earth building standard (DIN Norm), the basics of the hygrothermal behaviour, for example, in relation to potentials in heat protection or dynamic behaviour is missing. There are also limited methods to model the hygrothermal behaviour of heterogeneous structures in order to be able to validate the empirically determined performance and thus support the design process of earthen structures leading to higher market shares. The answer to the potential of earth as a high-performance building material which could reduce or even replace technical building equipment is still open. The well-being of the users in earthen buildings, which is often mentioned, has also only been examined to a very limited extent and requires further research. In the holistic view of sustainability, the material can do very well if it is left "pure" and not mixed with cement or chemical substances, i.e. reused endlessly in the life cycle or returned to nature at the possible end of life. Based on the knowledge which additives result in a weak environmental performance, those compositions that shown potential need to be exploited regarding their different applications. It offers potential to substitute common building materials which are made from non-renewable resources or cannot be reused or recycled to serve the same function. While earth products are increasingly available, the information on the physical properties of the products needs to grow in order to become easily integrated into the planning process.

The great potential of this material with regard to the physical properties of the building and the resulting possibilities to reduce building technology, especially ventilation and cooling technology, can only be reached with further research on the material level. The experiences with AM produced building elements and associated components made of earth are not yet very extensive and tend to be at the level of prototype development.

Partly automated prefabrication in the field of rammed earth construction, such as Martin Rauch e.g. practiced in the projects Ricola Kräuterzentrum and the Alnatura Arbeitswelt (Djahanschah, Auer, Kaufmann, 2020) is continued in the automation of rammed earth technology, which will open up greater efficiency in processing and new design options in free forms. After the first prototypical steps, further research is necessary.

The AM technology in the form of FDM technology opens up completely new potentials for designing solid earth wall components. While using different raw materials, eventually additives and aggregates and producing new spatial formations new wall systems are possible. The arrangement of air chambers enables the thermal resistance of the earth building materials to be optimized for winter performance. By designing the surface, in addition to the visual impression, the acoustic but also the hygrothermal effect of the elements can be improved.

Thanks to their structural design and the additives, AM earth elements (AME) enable a construction that is precisely tailored to the requirements. In this way, external and internal walls can react to different criteria of acoustic and sound insulation as well as to thermal and hygric ones. In connection with digital planning processes, customized elements and buildings can be manufactured.

The limitation of earth building materials lies in their load-bearing capacity. In Germany, solid earth buildings with up to two storeys are possible. There is great potential here in the connection to additively produced, optimized wooden structures. These are optimized for the statically necessary cross-section and enable new types of connections and automated production techniques in timber construction (Menges, Knippers, Wagner, Zechmeister, 2020).

In connection with wooden skeleton structures, AME can also find its way into multi-storey buildings. The combination of wood and earth was traditionally used in wattle and daub construction and is already known there for its good physical properties. The potential of both technologies can be joined by combining AME and automated timber construction. So far, the wood and earth construction has only been carried out by hand. Additive manufacturing techniques are suitable for components such as prefabricating complete walls in the workshops in the future and avoiding costly construction site production.

Through their further development until they are ready for the market, new types of construction elements are created which, on the one hand, can react precisely to new requirements such as climate change and, on the other hand, enable an economical construction method and thus distribution on the market.

8 CONCLUSIONS

In view of the interdisciplinary potential for sustainable architecture described above, it seems sensible to work on the topic of AME in greater depth. In particular the potential of complete individualization and the possibility of optimally adapting the structural design to the functional requirements with regard to load-bearing behaviour, climate, well-being and deconstructability promises to have a special influence on the performance of components and buildings. Furthermore, a targeted development of strategies for the transfer to the building industry is required, also against the background of the lack of experience with the combination of the technology, the lack of standards and the necessary exemplary application in order to create confidence in the technology.

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