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DOI
10.1016/j.buildenv.2021.108240

Publication date
2021

Document Version
Final published version

Published in
Building and Environment

Citation (APA)
Schweiker, M., Endres, E., Gosslar, J., Hack, N., Hildebrand, L., Creutz, M., Klinge, A., Kloft, H., Knaack, U., Mehnert, J., & Roswag-Klinge, E. (2021). Ten questions concerning the potential of digital production and new technologies for contemporary earthen constructions. *Building and Environment*, *206*, Article 108240. https://doi.org/10.1016/j.buildenv.2021.108240

Building and Environment 206 (2021) 108240

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Ten questions concerning the potential of digital production and new technologies for contemporary earthen constructions

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ARTICLE INFO

Keywords:
Earth
Indoor environmental quality
Health
Moisture adsorption
Digital production
Embodied energy
Circular construction

ABSTRACT

Earth is one of the oldest and till now intensively used natural building material. Around 30% of the world population still lives or works in buildings constructed out of earth. Most of them dwell in simple huts of rural communities or traditionally hand-crafted buildings. However, a growing number of people looking for healthy, environmentally friendly buildings in so called developed societies experience benefits of earthen construction materials. Due to the hygrothermal potential of clay, these benefits of earthen constructions include evaporative cooling during cooling periods and stable relative humidity levels indoors during the heating season. In addition, earthen building materials may contribute to the urgently needed circular economy, as earthen constructions like earth blocks or earth dry boards are reusable and earth plasters and mortars are replasticisable through the addition of water, as long as no chemical binder is added. Research gaps regarding physical properties, missing standardisation concerning building law and modern construction methods, and a limited number of manufacturers are hindering a wide application of earthen construction worldwide. Meanwhile, new digital production techniques evolve, which may elicit the potential of earth as future building material. Therefore, this Ten Questions article presents the state-of-the art and research gaps related to earth as building material in light of the potential of new digital production techniques like robotic fabrication or additive manufacturing. Such discussion includes new opportunities to combine the natural performance of the material with future-oriented construction systems and a new growing circular economy.

Introduction

The need to rethink the way we design, construct, and operate buildings in light of climate change, resource depletion, and waste generation is obvious. The construction sector accounts for around 40% of worldwide energy and process-related carbon dioxide (CO_2) emissions [1]. While building operation in the building stock covers a share of around 70% and building materials and construction of around 30% [1], the share of embodied greenhouse gas (GHG) emissions is increasing [2]. Raising awareness of these facts encourages researchers and other stakeholders to find solutions to decrease the environmental footprint of buildings and the construction sector.

The debate covers a multitude of aspects within the context of a buildings' lifecycle from reduced embodied energy and emissions in materials [3], over the operational demand to provide comfort and aspects as intelligent controls [4,5], design concepts increasing flexibility in usage to innovations related to the reusability of building components and materials. In this context and to achieve global climate goals, the

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https://doi.org/10.1016/j.buildenv.2021.108240
Received 6 May 2021; Received in revised form 22 July 2021; Accepted 6 August 2021

application of earth construction becomes increasingly interesting as the material itself and its various construction methods demonstrate very little environmental impact and cause hardly any CO_2 emissions [6,7]. From a global view point, the aim should therefore be to continue and improve the local building tradition and to make earthen buildings more durable with suitable construction measures. This could help to counteract, the growing application of conventional building materials with high embodied energy (e.g. bricks and concrete) in urban but also rural environments.

The share of houses built from earth is estimated to be around 30% [8] and also 30% of world population is living in earth-made constructions [9], while large regional differences exist. On one end of the scale, there are regions where earth as a building material is the dominant and nearly only available resource. In Peru for example approx. 40% of the buildings are earth constructions [10]. On the other end, in industrialised countries like the European regions have a low the number of buildings constructed with earth materials. However, the number of buildings made from earth increases slowly due to demands of sustainable, healthy, and comfortable living [11].

While there is not one specific reason for such low market share, several aspects could have caused the state-of-art. One reason especially in Europe could be the loss of knowledge regarding building techniques since the introduction of industrialised materials and technologies [11]. Another reason could be a low cost-effectiveness due to artisanal construction techniques. Historical earthen construction techniques are various due to cultural influences while for example in Europe techniques such as earth masonry and rammed earth as massive construction or as fillings in wattle-and-daub buildings are prevailing. In addition, earth is used as a cladding material in a variety of techniques and designs mostly as plaster but also as earth dry boards. All of these are based on artisanal construction techniques.

The low market share might have reduced the potential for innovations beyond such artisanal uses. With this respect, Kloft et al. [12] argue that cost effectiveness of buildings from earth can only be reached with (semi-)automated building processes. Therefore, the question is to what extent new manufacturing technologies such as 3D printing and robotics are able to unlock the potential for optimising the use of earth in the construction industry and whether they can contribute to the further spread of earth buildings. Thereby, the advantages of the material earth e.g. in terms of hygro-thermal characteristics need to be maintained.

Within this context, this Ten Questions paper deals with the combination of a very traditional building material – earth – with high-tech advancements in fabrication and application methods – digital production technologies. The objective is a multi-dimensional discussion of such new technologies for leveraging the potential of earth as building material. In addition to the technologies themselves, main aspects considered are the indoor environmental quality (IEQ), user satisfaction, and circularity of earthen constructions.

The paper is structured as follows. Initially the state of art in standardisation, influence in IEQ and advances related to circularity are summarised (Q1-3). Questions 4 to 7 introduce new technologies and future potentials related to the industrialisation potential. Human satisfaction and health, circularity and an updated formal language are discussed in Questions 8 to 10. The final section summarises the ten questions and answers and concludes with further research needs.

1. Question 1: What is the state of the art of the building material earth regarding standardisation?

In many regions of the world, especially in countries of the global south, earth is usually extracted locally as a traditional building material and processed manually by artisans based on an in-depth experience. Such buildings are constructed on the basis of tested materials and construction methods instead of approved building standards. The accrued knowledge has been passed on over centuries from one generation to another [6,7]. In industrialised countries, constructions are carried out in a similar artisanal manner, primarily in the field of monument conservation but also for new constructions like residential, office and public buildings, supported by available local standards (e.g. the German "Lehmbauregeln", the earthen building rules [13]).

Due to an increased interest in sustainable and healthy construction in many countries of the world, the number of earthen constructions is rising in recent decades. This development has triggered a growing number of earthen building codes, guidelines and standards worldwide, providing a varying degree of technical information such as building materials and techniques (adobe, rammed earth, compressed earth blocks etc.), in-depth material properties (composition, strength, safety performance etc.) and local conditions [6,14]. However, in comparison to other construction materials and methods the overall number is still fairly low [6].

In Germany, the development of standards for earthen construction has a long tradition and goes back to the 16th century [15]. In 1951, DIN 18951 was introduced, regulating design concepts and material parameters for the verification of stability [13]. After German standards have been withdrawn in 1971, Peru introduced the first standards for unstabilised and stabilized adobe construction in 1977, replaced by an updated version in 2000, covering site conditions, calculation criteria, seismic design etc. [13,16]. New Zealand was one of the first countries that introduced a more comprehensive set of standards for earth buildings in 1998 covering engineering design, materials and workmanship of earth buildings [17–19]. With the Lehmbauregeln from 1999 [13] and the DIN standards from 2013 to 2018 respectively [20–23], Germany provides detailed regulations for four earth building materials covering amongst others the range of application, application classes, testing, mechanical strength, fire and sound protection [15,20–23]. Also other countries like Brazil, India, US (New Mexico, California), to name a few, have composed standards or technical documents that vary regarding the degree of technical information. The standard in India, coming into force in 1980 and being updated in 1993 covers the improvement of earthquake resistance of unstabilised earthen buildings constructed from adobe or rammed earth limiting the building height to one or two stories in relation to the seismic zone [24], whereas New Mexico deals with cob wall construction only. The standard approved in 2019 is part of the international residential code (IRC), which is used in 49 of the 50 US states, as Appendix U 'Cob Construction' and covers one- or two-family dwellings [25]. Overall earth building standards can be found in more than 20 countries, on all continents [6]. However, an internationally accepted terminology as prerequisite for the development of standards is still lacking [6].

In addition, a lack of standardisation of both products and constructions exists, even though there are many manufacturers that offer certified earthen building materials. In order to increase the market share of earthen materials and constructions, it is important to provide standardised, industrial products, manufactured in a regulated way. The success can be observed, as standardised products from the ecological building materials market are increasingly being used, with a steady annual growth in the low double-digit million range [15].

2. Question 2: What is the influence of earth constructions on IEQ and HVAC equipment?

Earth as a construction material is compared to many other building materials porous and vapour active to humidity from the air. This characteristic offers the opportunity to enhance IEQ while reducing active energy demands from heating, ventilation, and air-conditioning (HVAC) equipment [26]. Earth, like many other mineral based building materials, has a high thermal capacity, which supports passive design strategies with natural ventilation. The well-understood self-regulating effect with respect to thermal conditions reduces temperature peaks by buffering heat or coolness. Additionally, earth has the ability to absorb high amounts of water from the air. Depending on the humidity gradient between air and a porous material this additional self-regulating effect can be adapted to vapour transmission reducing energy demands of active systems which is usually not considered in the design process [27–29]. Combined with materials having insulating properties, such as hybrid wooden structures or in combination with porous mineral aggregates (e.g. foamed glass), earth is interesting for colder climates with lower fluctuations in relative humidity rates [30].

There is only a limited evidence for the optimal hygrothermal operation of earthen buildings which show the potentials on reduced active energy demands and loads besides some standardised tests for material properties. Sorption processes and accompanying material properties are standardised for only some earthen products e.g. earth mortar [22]. During a constant air temperature of 23 °C a rise in relative humidity from 50 to 80% is induced while the control volume is weighted continuously to identify the adsorption of moisture during at least 12 h. Tests show that the ability to adsorb moisture from the air is 9 times higher compared to constructions from concrete [11]. Still, the authors believe that the knowledge that earthen constructions do effect the room comfort is present but can rarely be quantified in the design process. A reason could be that only few tools for dynamic simulations can calculate sorption processes or even pollutants combined with locally varying properties of earthen building materials [31,32]. This goes along with limited heuristics such as rules and recommendations to control the indoor relative humidity which are easy to apply (such as night flushing for temperature shifts). One approach could be to establish combined coefficients affecting IEQ. An example for such a coefficient is the Moisture Buffer Value (MBV) [33]. The MBV describes the change in mass of moisture per surface area and the change of relative humidity from the air during a defined cycle of 8 h while ventilation rates and other effects on the indoor climate are not considered. Rempel et al. [28] describes another effect called intrinsic evaporative cooling of vapour active constructions. This effect was studied by model simulations which leads to cooling capacities from 5 to 15 W/m^2 for different earthen construction materials. Considering the operation under real life conditions, the ability of humidity sorption from the air into earth dry boards is 3–5 times higher compared to plasterboards made of gypsum [34]. An earth dry board with a thickness of 20 mm adsorbed 100 g/m^2 of humidity after 12 h compared to 20 g/m^2 by a gypsum board with a thickness of 12.5 cm. It can reasonably be concluded that the self-regulating effect of the air temperature is also applicable to a self-regulation in relative humidity [35].

Considering the local climate during the design process and hygrothermal material properties (sorption, thermal capacity and insulation), earth has the potential to reduce the demand of technical equipment [36]. For example, the risk of mould due to peak-loads of moist can be compensated by the ability to absorb humidity quickly [31]. Hence, extended ventilation rates of peak loads can be reduced. A field study based on two residential buildings which are operated within German climate conditions – one is built from materials without moisture buffering potentials whereas the other one is built from natural materials such as earthen plaster and wooden fibre boards – showed a significant difference in humidity levels [34]. Within the second building made of natural materials humidity levels ranged at almost 40%–60% relative humidity during a whole year, which is a spectrum providing healthy and comfortable conditions (see Q8) whereas the buildings made of conventional materials showed lower rates in relative humidity with higher alterations leading to the need of active humidification.

Another potential of earth when covering the indoor surface lays in its ability to improve the indoor air quality (IAQ). Research suggests that eco-materials have the potential not only to reduce emissions of potentially harmful substances into the room air, but also to adsorb for example specific volatile organic compounds (VOCs) [37]. Similar processes have been observed for clay plasters being those that had the best results in terms of adsorption of airborne pollution, increasing the potential to reduce ventilation rates [38]. Still, research in this area is in general scarce and deserves further attention.

3. Question 3: How circular are building products from earth?

Circularity is a term not defined in standards. Relevant stakeholders, who attempt to evaluate design decisions and quantify circularity, are the Dutch platform CB23 [39], the Ellen MacArthur Foundation [40], universities e.g. RWTH Aachen [41], or architects and engineers [42]. The extend of circularity of construction materials can be described by using two categories which are: 1) the material which is or is becoming part of the construction (input) and 2) its post-use potential (or potential output) [41,42]. Different methods are available to specify and quantify circularity and most of them work with the analysis of input-output categories, which is followed here.

Input. The goal in the category input is to provide a product which embodies as little energy and emissions as possible to the production. Earth products are most commonly used in near proximity and processed by hand or supported by machines. This can avoid the landfilling of excavated soil and preserve resources. Manufacturers for earth products work with disposal enterprises to integrate the excavated soil into production process an instead of storing them on landfill [43,44]. Earthen building materials offer a very high potential for the reduction of mineral construction and demolition waste. Especially for the fine fraction <2 mm applications are urgently needed as such waste streams are diverted to land fill, as current standards for RC concrete and earthen building materials do not permit such grain sizes to be integrated as aggregates. Current research demonstrates the technical feasibility of the approach and with relatively high recycling rates of 67%–87% in relation to the earthen material [44]. The Ricola Herb Centre by Herzog & de Meuron with Martin Rauch is a well-documented project using locally harvested earth materials which are processed in close proximity and integrated in the construction [45]. This is beneficial to the energy consumption and emission production linked to the transport and the production of earth products. This results in low values for global warming potential ranging for rammed earth from 0,004 [6] to 0,02 [46] kg CO2 eq/kg and for compressed earth blocks from to 0,06 [6] to 0,08 [46] kg CO_2eq/kg which is approximately 25 times less than concrete with 0,10 kg CO_2eq/kg. These include raw material supply, transport from raw materials source to factory and processing (A1-A3 according to EN 15804 [47]). When using life cycle assessment data, the functionality needs to be considered in order for a fair comparison with other building materials. Especially the material thickness needs to be factored in. While solid construction from bricks, limestone, or concrete with insulation typically result in thicknesses from 25 to 40 cm, a wall with the same functionality from earth will need 40–70 cm. Comparing the GHG emission for the input, the wall from earth will (when produced with low-tech) result in significantly lower (around factor 10) values even with the increased material amount [6].

The production and functionality can be improved with automated processing. However, the environmental impact grows when machine work is used for the production of earth products. Studies by Arrigoni et al. [48] or Fernandes et al. [46] present the extend of ecological impact according to the life cycle phases and show that most emissions occur in production. Environmental data on automated processes were investigated in a study on deconstruction of facades [41]. The processes are comparable to producing rammed earth. It shows that the machine efficiency is key for the environmental impact with the logic that older machines (robots) use more energy. The time needed to perform the task and machines engine power contribute in the same way. With growing share of renewable energy for electricity, the authors believe that the environmental impact linked to emissions can be reduced significantly.

Considering the resource that form the construction, printing provides the advantage to only use necessary material which can potentially reduce the overall resource spend on a construction.

Post-use potential. This category describes the possible applications after the use phase ranging from reuse as component over pure and mixed material recycling to incineration and landfill. Additionally, the processing should produce as little as possible emissions especially in comparison to the original product. The effort for deconstruction depends on the building properties (mainly height and accessibility) and the product composition. In a dense, urban context, a building with a large height will be more difficult to selectively built back than one with large surrounding areas where for example containers for different material fraction can be placed [49].

Reuse of earth products seldom applies due to the brittleness of the material. Bricks can be reused by different techniques but are not discussed within the scope of this paper. Prefabricated components (e.g. timber modules with earth filling) have the potential to be reused as the systematic construction provides detachable joints with recurring details [50].

The product composition impacts the recyclability. While pure material can be used for new products [6], components with stabilizer need further treatment (such as crushing, sorting) and depending on the type of stabilizer not all of the material will be suitable for recycling (for example the cement will be downcycled). The usefulness of stabilizers needs to be evaluated in the context of the building elements required robustness [48].

For deconstruction in an industrialised context, machines for cutting, lifting and sorting are used similar to the disassembly of mineral building products [41]. Decentral machines are often smaller compared to stationary ones which can lead to longer processing, but transport is more efficient when material is crushed on site [51].

4. Question 4: Which are new digital production technologies of additive manufactured earth constructions and their relevant technical parameters?

Complementing traditional production methods, new digital manufacturing processes are opening up new avenues for earthen construction [52–56]. On one hand, the use of computer-controlled machines enables a more efficient production of earthen structures, that would otherwise be too cost-intensive due to their artisanal production. On the other hand digital fabrication techniques, expand the geometric freedom and thus enables advanced functional integration and new expressive forms of design. Some of the new digital fabrication methods described here are based on traditional earthen building techniques, but significantly expand their formal capacities and fabrication accuracy. A selection of innovative digital manufacturing methods including automated extrusion, robotic rammed earth, and robotic sprayed earth, including their technical parameters, are described below.

4.1. Automated extruded earth

One of the most intensively studied digital production method for earth is extrusion [57]. While initial experiments involved 3D printing pottery with clay [58], concepts have recently been developed to take 3D printing with earth-based materials to the scale of architecture [59]. Approaches range from 3D printing smaller brick-like components (Fig. 1a) that are subsequently assembled into buildings [60,61] (Fig. 1b), to monolithic printing of entire buildings using house-sized 3D printers and locally excavated material [62,63] (Fig. 1c).

Earth extrusion is based on the principles of fused deposed modelling (FDM). A strand of clay is positioned robot controlled on top of former layers, which creates the geometry of the object. Depending on the diameter or geometry of the extruder head, size and speed of the production is defined. Stability of the object during production is related to the material parameters and geometry. The specifications of the printer are a decisive factor for the viability of the designed geometry. For example, robots and gantry cranes enable different component sizes with varying geometric complexity and precision. A second group of parameters concerns the material to be printed. For example, the size of the extruder determines the maximum particle size of the clay; the maximum extrusion speed depends on the fluidity of the material; and the stability of the material after printing determines whether it can be used with or without support material. Following the subsequent printing process, the object must be subjected to controlled drying. As such, in order to avoid stresses in the component this drying process might have to be regulated. Later handling and transport also constrain the geometric dimensions (width, depth, and height) of the printed objects [64–66].

4.2. Robotic rammed earth

Robotic rammed earth is based on the traditional method of rammed earth production, in which earth is mechanically compacted to such an extent that load-bearing and durable structures are created. For the traditional method of production, layers of an approximate height of 10 cm are placed in a formwork and are subsequently compacted using hand operated rammers [11]. Nowadays, pneumatic compaction machines are increasingly used [6]. In addition to the high labour intensity involved in compacting the soil, the amount of labour and material required for erecting the formwork is also very high. To reduce this cost factor and further increase manufacturing efficiency, automated manufacturing processes for standardized rammed earth components

Fig. 1. Digital Fabrication with Earth using automated extrusion: (a) Functionally integrated 3D Printed Brick, Institute of Structural Mechanics and Design, TU Darmstadt; (b) Assembled 3D Printed Bricks, Digital Adobe, IAAC Barcelona (©IAAC, 3DPA wall prototype "Digital Adobe", 2018); (c) Monolithic structure printed in situ, Project Telca, Wasp (©WASP).

are already available on the market. In particular, the rammed earth machine "Roberta" from Martin Rauch should be mentioned here, with which straight wall elements can be compacted and cut to size semi-automatically [64,67].

Moreover, with the robotic rammed earth method, the focus is not only on increasing the geometric degrees of freedom, but also on further minimizing the material and labour requirements. Here the formwork is reduced to a minimum and consists only of a robot-guided slipform. The soil is automatically transported onto the compacted layers by a CNC-controlled feeding device and compacted by a heavy vibratory plate [12] (Fig. 2). The size of the slipform has an influence on the geometric possibilities, by reducing the size of the formwork to a minimum, while maintaining sufficient support during compaction, curved elements are theoretically possible. The layer height is dependent on the rigidity of the slipform due to the fact that the pressure introduced to the slipform raises with ascending layer height. Moreover, the shape and general mode of operation of the compaction device are influencing the layer height. The optimal process speed is determined by the compaction frequency and force of the vibratory plate, which again is dependent on the feeding height of the raw material. The velocity of the compaction process needs to be well adapted to these parameters, as a velocity that is set too high might lower the degree of compaction.

Robotic sprayed earth. Robotic sprayed earth is based on an adaptation of a manual earth spraying process called "Pneumatically Impacted Stabilized Earth" (PISE) [6]. Here a dry cement-clay mix is conveyed by air pressure to the spray nozzle and mixed with water as it exits the nozzle (Fig. 3a). The mixture is sprayed with high pressure up to a thickness of 60 cm against a single-sided wooden formwork. For earthquake resistance, a conventional steel reinforcement cage can be integrated. The open side is leveled with a smoothing trowel after spraying [68]. Experimenting in digital design and fabrication, French architect Stéphanie Chaltiel has developed a process in which a flying drone sprays soil onto lightweight textile formwork [54]. The goal of the project is to build emergency shelters in disaster areas (Fig. 3b).

Another approach, for completely formwork-free 3D printing with sprayed earth, is based on Schotcrete 3D printing technology [69] (Fig. 3c). Instead of laying extruded paths on top of each other, a target geometry is produced here by spraying layers of earth in a layer-wise manner. In preliminary tests, structures with a layer width of up to 15 cm and a layer height of up to 2 cm were produced. Due to the projection of the material layer via compressed air, a high degree of compaction of the earth is achieved. Besides the good bond between the layers, the process offers the possibility of adding chopped natural reinforcement fibres to the material in flight. The addition of fibres and natural additives can positively affect the shrinking behaviour during drying, and the mechanical strength of the material [11,70,71].

The technical parameters which are influencing the robotic spraying process are the water content of the earth mix, the type, size and volume fraction of the fibres, the air pressure, and the spraying distance. In terms of geometric freedom, the earth spraying process is less limited than the robotic rammed earth process, but more constrained than the automated earth extrusion method. Similar considerations can be made about the maximum compressive strengths that can be expected, with robotic rammed earth being the strongest and automated extruded earth being the weakest.

In summary, the reciprocal influences apply to all digital manufacturing methods with earth, but they vary depending on the manufacturing method used.

5. Question 5: How can the construction quality of earthen constructions be improved by using digital fabrication technologies?

Earth is a locally sourced, non-standard material that varies greatly in its material composition and performance depending on local conditions. Moreover, earthen constructions are mostly produced in situ using manual processes, introducing additional uncertainties to the process. The question is to what extend a controlled material-process-interaction through adaptive digital manufacturing methods could significantly improve the quality of earthen constructions. Key parameters that can be influenced are erosion behaviour, material properties, construction tolerances and deviations, and the visual surface quality.

Erosion behaviour. The erosion behaviour has a significant influence on the durability of earthen materials, which is threatened especially by direct exposure to water. Historically, water induced erosion of earthen construction is prevented by constructive measures such as large overhanging roofs and suitable footing. In addition, lime renders were frequently used to further protect exterior walls. However, wind driven rain, as a function of the rain impact-angle and the absence of overhanging roofs promote the erosion of weather exposed earthen constructions [72], leading to reduction of the component's width, and therefore its mechanical strength. In the case of rammed earth Martin Rauch introduced the concept of "controlled erosion", which incorporates the natural erosion in the design process by providing excess material that erodes in a controlled manner on water exposed surfaces [73]. The material mixture used presents a broad spectrum of particle-sizes, the finer particles are washed out over the years and the coarse grain gradually emerges on the surface, which eventually stops the erosion process. The absence of large particles such as gravel and stones in extruded and sprayed earth can be seen as a disadvantage in

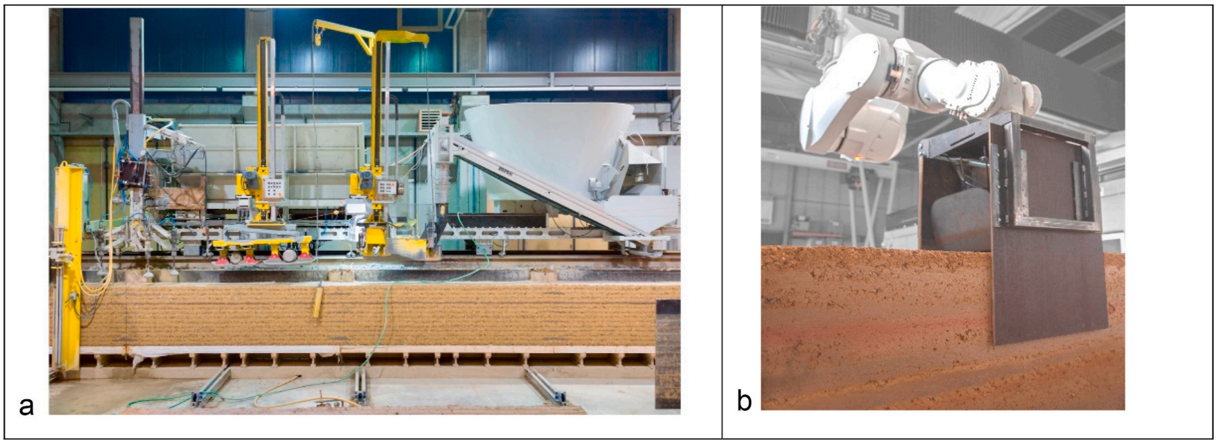

Fig. 2. Automated production methods for rammed earth: (a) "Roberta", machine for the production of straight wall elements (© Lehm Ton Erde Baukunst GmbH / Emmanuel Dorsaz); (b) Robotic rammed earth, a robot guided slipform requiring a minimum of formwork during compaction, Institute of Structural Design, TU Braunschweig.

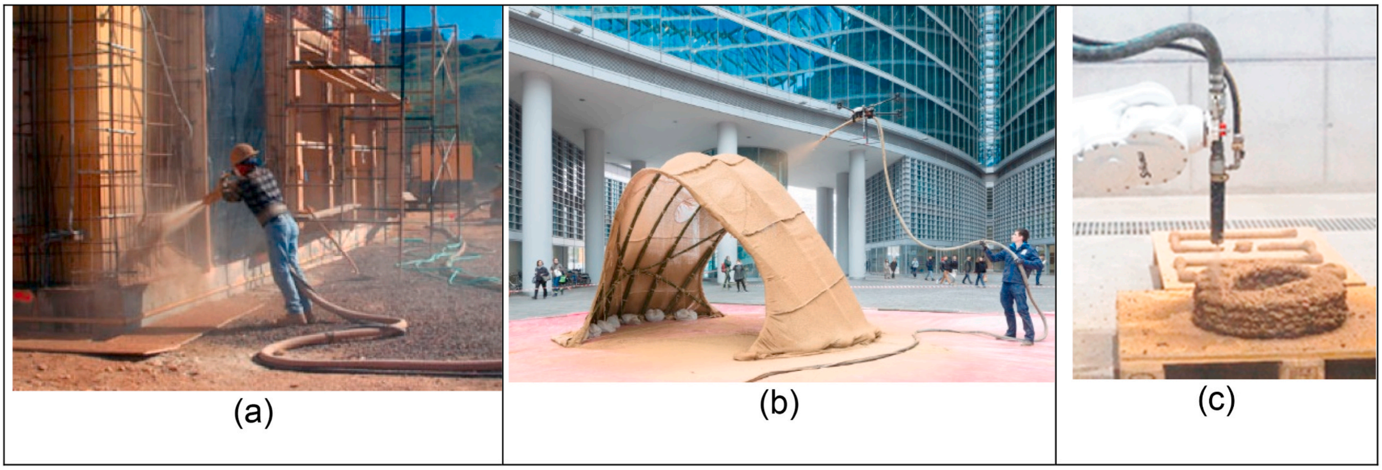

Fig. 3. Sprayed Earth Structures: (a) Pneumatically Impacted Stabilized Earth (©Tagungsband LEHM 2008 Koblenz, Beiträge zur 5. Int. Fachtagung für Lehmbau); (b) Drone spraying earth material onto a textile formwork (©NAARO/courtesy MuDD Architects); (c) Robotic Sprayed Earth, Institute of Structural Design, TU Braunschweig.

terms of erosion resistance on weather exposed components. However, digital fabrication allows for functional gradation of the composition through digitally controlled deposition of varying types and ratios of aggregates. Hence, erosion properties can be influenced by means of controlled integration of water-resistant aggregates and injection of admixtures, where they are needed [74]. By assessing suitable admixtures for earthen materials, performance-gains and ecological compromises need to be weighed carefully, in order to avoid putting the materials cradle-to-cradle recyclability at risk [75]. For example, Muguda et al. obtained promising durability results by using biopolymers (guar- and xanthan-gums) as stabilizers for 3D printed earthen materials [71].

Material properties. The mechanical strength of earthen materials is dependent on several properties, such as cohesive strength of clay content, moisture content and dry density. The dry density however depends strongly on the material composition, hygroscopic properties and adequate densification executed in the manufacturing process. Especially the consistency of material deposition and densification introduced to the material is hard to control on a construction site, leading to high fluctuations of material properties [76]. Recent experiments at the Institute of Structural Design, TU Braunschweig (ITE) showed, that digitally controlling the feeding and compaction process (e.g., in the case of rammed earth constructions), can cause a mitigation of inconsistencies during construction and therefore lead to an increased

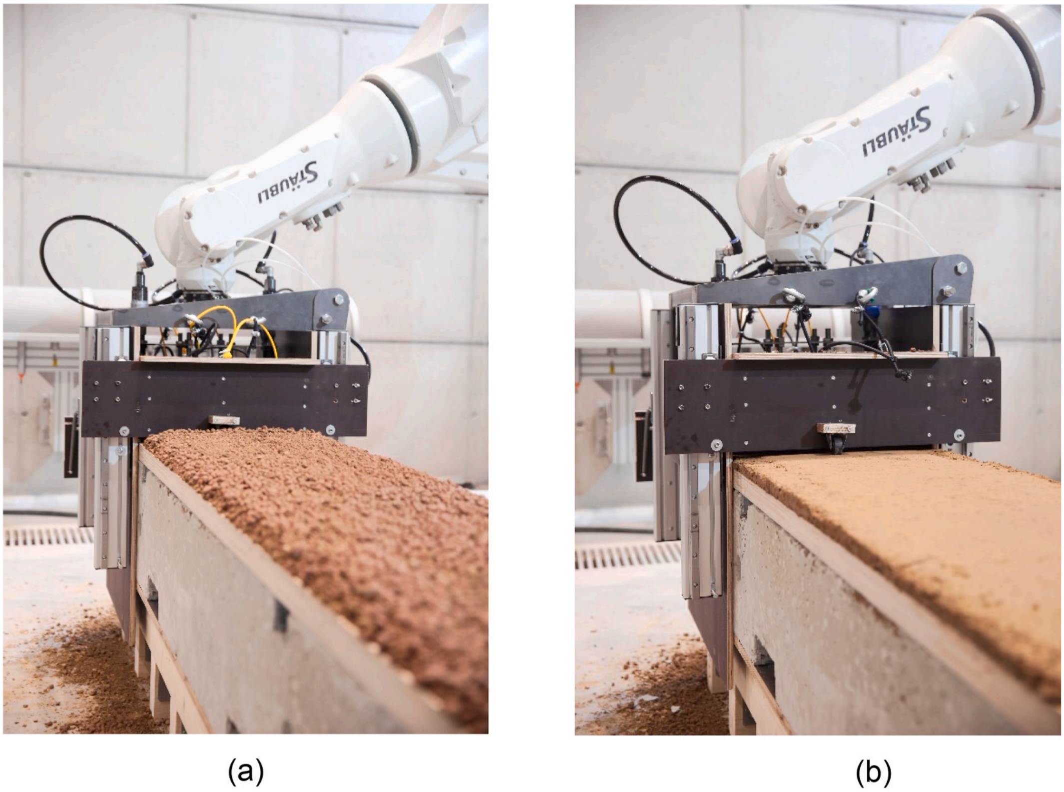

Fig. 4. CNC-controlled deposition of the raw material to a consistent height before (a) and after compaction (b) in the robotic rammed earth process, Institute of Structural Design, TU Braunschweig.

coherency of material parameters and increased safety. For example, in robotic rammed earth manufacturing, the feeding height of the raw material can be digitally determined and therefore deployed to an either consistent (Fig. 4), or variable layer height. The following compaction process can be influenced, by controlling the parameters such as time, frequency and energy of compaction in order to ensure optimal compaction results. The shape of the layers might have a considerable effect on the bond of the interfaces between the layers. According to Bui and Morel [77], rammed earth material can be considered as an isotropic material within one layer. However, the interfacial bond between the layers appears to be the weak point resulting in a lower shear strength parallel to the layers compared to the shear strength perpendicular to the layers [78]. Thus, a variable layer height might be desirable from a structural point of view.

Tolerances. In earthen construction, it is generally advised to allow higher tolerances compared to well established industrial materials such as brickwork or concrete [79]. Concerning rammed earth, for example a deviation of −20/+40 mm from the designed wall thickness is advised, which leads to difficulties in detailing concrete [79]. The precision and quality of earthen constructions greatly depends on the shrinkage behaviour of the earthen material, as shrinking can cause deviations from originally planned dimensions and can lead to cracks [80]. Prefabrication allows for controlled climatic conditions during manufacturing and drying, which benefits a mitigation of defects caused by shrinkage. Additionally, digital fabrication techniques enable possibilities of subtractive reworking after drying or in the materials fresh state. Therefore, the precision of additive and subtractive digital fabrication techniques allows to fabricate building elements with tighter tolerances and thus allows a simplification of the planning and execution process of the subsequently following trades. With the implementation of online quality control through 3D scanning, the overall precision can be further enhanced: The scanned data can be compared with the reference data and – if required – be reworked, which results in precise shapes according to the digital model.

Surface quality. In traditional earthen constructions, the surface of the element is usually hidden by a formwork until it is removed after manufacturing. As a result, surface defects come to light only after finishing the manufacturing process, entailing a time-consuming subsequent correction of the fabrication defects. Novel concepts of digitising earthen construction include downscaling of the necessary size of formwork by using an active, robotically controlled slip form [81] or deleting the concept of formwork by extruding the material. Besides the effect of using less material for production, a smaller formwork enables the opportunity of direct access to the manufactured element during fabrication, whenever needed, leading to better quality-control during manufacturing. Hack and Kloft showed, that the surface quality of digitally manufactured components can be influenced to a significant extent by means of subtractive post processing methods, either in the materials green state or after drying [69].

6. Question 6: Which new requirements arise for the raw material to be processed with digital production methods?

For many construction materials including earth, the material and the manufacturing process are closely interrelated and often the requirements are even mutually dependent. In the past and present, material evaluation and grading for earthen constructions are done by specialists through visual inspection, haptic assessment and the evaluation of test specimen. In digital fabrication, the analysis of the raw material remains crucial in order to adapt the parameters of the manufacturing process and ensure optimal manufacturing results. To synchronize the material and the manufacturing process there are two possibilities of which one is to create specialized, industrialised materials fulfilling the demands of the production process. As a drawback, this approach leads to the need of industrialised, premixed raw materials and therefore compromise the great potential of using local soil excavated directly from the construction site. The other possibility is introduced by the digital fabrication techniques, which enable the possibility of controlling the manufacturing parameters online through sensor integration and real-time feedback (e.g. on the state of compaction). Hence, the local material can be analysed and the process can be adapted according to the materials demands.

The correlation between the manufacturing process and the performance requirements for the raw material is related to the freedom in design. More design freedom demands less material support (such as shuttering) during the manufacturing process, which consequently creates higher self-supportive requirements on the raw material. For example, the robotic fabrication of rammed earth elements using an active slip form [82] has comparatively high support through the formwork. Consequently, it entails a relatively limited design space and low demands on the material. Comparable to manual rammed earth processes, optimal densification and stability is reached by suitable particle-size distribution, well synchronized with the manufacturing process in order to ensure best possible compaction results.

The reduced layer height in the robotic rammed earth process leads to a reduced applicable size of the coarse grain in the raw material. Recent tests on the mechanical properties show comparable results in compressive strength for robotically and manual fabricated rammed earth, the main advantage here lays in the possibility to achieve consistent mechanical properties, deriving from consistent process parameters.

Processes with less support during manufacturing require raw materials that are more specialized regarding the performance -of the material. The optimum values (e.g. type of clay, water content, particle-size distribution) need to be identified according to the process the material is designed for. For example, the clay material must be pumpable for spraying and 3D printing without compromising green strength, which describes the strength of the material immediately after extrusion, or shrinkage behaviour during drying. Thus, both techniques demand for pasty and invariant consistency of the material, in order to ensure a continuous material-flow during extrusion or spraying. For example, extruding or spraying earthen materials does not involve any kind of external shuttering, thus the demand on the raw material is high: it must be pumpable, without adversely affecting its green stability or shrinkage behaviour during drying.

Water content, particle size distribution, and the addition of admixtures play a major role while adjusting the right mixture. The freshly mixed material must be fluid enough to be pumped, and stable enough to sustain the weight of the subsequently deposited layers. The addition of specific bio-based admixtures can improve the accountable material properties. For example, Perrot et al. significantly improved the materials green strength in fresh state by adding alginate seaweed biopolymer to the mixture. The effect of stabilisation is measured by means of deformation of the first layer at a building rate of 1 m per day (24 h). For this building rate, the deformation of the first layer is extrapolated to 17% without admixtures and 1,7% with the use of alginate [83].

Another important characteristic, defining suitable earthen materials is the particle size distribution, which for 3D printing should present mostly fine particles with a ratio of pipe to maximum particles diameter of around 10 [83]. The high water content of around 45% can lead to cracks caused by shrinkage during drying. The addition of admixtures such as natural fibres [80] and biopolymers has an impact on the materials mechanical properties and offer a promising approach in order to mitigate defects, caused by shrinkage and increase the materials green strength [83]. For robotic rammed earth, an automated conveying of the material and suitable particle-size distribution in order to ensure best possible compaction results are important [82,84].

7. Question 7: How can new (digital) automation technologies advance the industrialisation of earthen constructions?

A specific feature of building with earth is the use of local building material, extracted either directly from excavation on site or from the immediate surroundings of the construction location [6]. In traditional earthen construction, the locally extracted raw material is manually processed into monolithic structures on the building site [6]. As with most in situ construction processes, this labour and cost-intensive building process is influenced by a certain level of inaccuracy, the exposure to changing weather conditions, and the skill of the involved craftsmen [79].

One method of counteracting the disadvantages of traditional in situ processing is the industrial prefabrication of earthen building components. Next to other examples [85,86], the artisan Martin Rauch has developed a prefabrication system for this purpose, with which earth components can be mass-produced on or near the building site using local raw materials [67,87]. Elements are manufactured off-site with semi-automated ramming equipment, transported to site and craned into position with a relatively high precision. The final reworking of joints and surfaces is, however, still labour-intensive, as it is carried out manually [36].

In several projects in Austria, Switzerland, Saudi Arabia, and Germany, near-site field factories were installed, where the elements were manufactured and subsequently assembled on site. The main advantages of prefabrication near to the construction site are the independence from weather conditions, which shortens the construction time on site and makes the construction time predictable. Moreover, local soil can be used which results in short transport routes. These are important parameters when talking about an industrialised construction process for earthen materials [67].

In the “Alnatura Campus” project in Darmstadt, such a field factory was set up near the construction site. The temporary prefabrication plant has already been used in previous projects and consists of a compulsory mixer for moistening the pre-mixed raw material and a movable 1-axis feeding device for feeding the material into the 50 m long formwork, which originates from concrete construction. Compaction is carried out with an automated pneumatically driven rammer. After compaction, the monolithic component is cut into 3.5 × 1.0 m elements with a water-cooled digitally controlled circular saw. These elements are then transported by crane to a storage space where they dry under controlled conditions [67,88].

While prefabrication on site brings clear advantages in terms of component quality, manufacturing efficiency, and a significant reduction in construction time on site, this method is limited in terms of geometric freedom due to serial production.

An advancement of industrial prefabrication with earth, based on similar concepts as the precast concrete industry, can be seen in digital in situ fabrication. Here, digitally controlled machines equipped with sensors produce entire building structures directly on the construction site [89,90].

Digital in-situ fabrication allows the combination of the advantages of the two previously discussed fabrication methods. Individualised components can be manufactured efficiently and cost-effectively with industrial precision directly on site, completely eliminating the need for formwork and on-site assembly processes. One example of such digital in-situ fabrication with clay is WASP technology [56], in which a stationary (but moveable) device with synchronized printing arms allows for the in situ fabrication of 50 m^2, single story rooms per printing head. In a combined application, the printers are able to fabricate larger structures as shown in the TECLA project by WASP and Mario Cucinella Architects [91], where local material was used in combination with water, rice husk, straw fibres, and around 5% of lime as a binder [92]. The preparatory measures include the excavation of the local material and subsequent material analysis conducted by specialists, which is the basis for the addition of water, fibres and additives. With the TECLA setup, a two room, one story house was printed within 200 h (see Q4, Fig. 1c).

However, digitised construction processes, especially for non-standard building materials such as earth, have not yet reached a level of industrialisation suitable for the mass market. In the future, cyber-physically interconnected, intelligent production systems could pave the way for an industrialisation on a large scale. Digital production facilities equipped with sensors promise to process even non-standardised materials more precisely and robustly by being able to react dynamically to changes in the production process [93]. Furthermore, the collection of production data, the documentation of production conditions and production results in cross-linked digital databases could enable an expressive and diverse construction language similar to traditional craft techniques on an industrial scale [94]. Therefore, we believe that new digital production techniques will give earthen buildings a future through innovative construction rather than through more efficient processing.

8. Question 8: What is the potential of earth constructions for human well-being and health?

The IEQ and the HVAC equipment affect human health and satisfaction within indoor environments. Individual aspects of IEQ such as indoor air quality (IAQ), temperature, and humidity levels alter physiological reactions and subjective satisfaction and well-being [95]. For example, poor IAQ is a known indoor related health-risk associated with respiratory and other diseases [96]. High indoor temperatures and humidity levels increase the thermal strain under warm and hot summer conditions especially for vulnerable persons [97,98]. Respiratory health effects during wintertime are fostered by rather low relative humidity levels due to the heated room air [99] and humidity levels between 40 and 60% are considered beneficial for the respiratory health, while not affecting IAQ through mould growth [100].

The hygro-thermal characteristics of earth described in Q2, which are enhancing the reduction of thermal peaks and balancing humidity levels, offer a large potential to reduce corresponding health effects and to improve user satisfaction and well-being indoors. However, studies looking specifically at the effect of earth materials on user satisfaction and health are scarce. 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 revealed 37 journal articles of which only 11 were suitable after re-viewing their content in detail. 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, a summary of their findings enables the identification of potential effects.

Studies can be grouped into those looking at direct and indirect effects. As for direct effects, Li et al. [101] studied traditional Chinese Tulou buildings made of rammed earth in a wooden framework and close by “normal rural buildings”. Based on 139 questionnaires from 6 Tulou buildings and 97 responses from an undefined number of normal buildings, they observed higher thermal satisfaction with the Chinese Tulou buildings compared to normal rural buildings. However, differences in building materials, architecture and style of buildings limit cause-effect conclusions. Based on measurements and subjective votes of 5 respondents in a single rammed earth building in Portugal, Fernandes et al. [102] concluded that thermal performance was satisfactory during summer, but heating was required in winter. No control condition existed. Comparing one building with traditional solid rammed earth walls with one other building with rammed earth walls including an insulating polystyrene core in Australia, Beckett et al. [103] found high thermal satisfaction rates in winter and summer in both buildings. Noteworthy, there were only short periods with heating demand in winter and occupants’ ratings exceeded predictions by calculated satisfaction indices. The application of above described technologies opens further opportunities to influence IEQ positively. These opportunities include the potential of earth plaster optimising acoustic properties beyond sound insulation through surface properties enhancing sound absorption, while keeping thermal mass activated; increasing perceived IAQ due to lower air temperatures known to be perceived as more fresh [104]; and an improved visual environment through enhanced visual properties of the surface minimizing glare through reflection.

Indirect effects of earth constructions relate to the perception of working or living in a building with natural materials. Cause-effect relationships are even trickier to be established and evidence so far is based on case studies partly contradictive and not systematically assessed. For example, Deuble and de Dear [105] concluded that occupants in ‘green’ buildings accept conditions outside classical comfort ranges more likely than occupants in conventional buildings. This is in line with the studies by Ref. [106] and Leaman and Bordass [107] who found strong positive effects of ‘green’ buildings on user satisfaction compared to conventional buildings. In contrast, Taylor et al. [108] found no difference in occupants perception with respect to thermal, visual, and acoustic aspects comparing one rammed earth building with one other conventional building. Overall, small sample sizes compared to the large variety in human perception and preferences do not permit final conclusions and ask for further well-designed research endeavours.

In addition, other important influences on human satisfaction with IEQ have not been addressed with respect to earth buildings. One such influence is perceived control, which is associated with positive effects on user satisfaction based on studies in conventional buildings (e.g. Refs. [109,110]). Therefore, a buildings’ capability of self-regulation should not reduce control opportunities for individual comfort.

A side note shall be added looking at interesting side-effects of building with earth and “feeling earth” on human health. Wong & Au [111] concluded that participants (n = 36) 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 [112] compared earth art therapy with visual art therapy and found a positive effect of earth on emotion regulation and other aspects of mental health in adults with depression (n = 106).

The use of additives and its effect on the above-mentioned aspects is not well studied [32]. On the basis of additive manufacturing (AM) and automated construction techniques, the surface texture itself could be optimized also from a perspective of the IEQ. This optimization could be achieved with an increase in surface area through a roughened texture by digitally controlled fabrication techniques as described in Q4 to 6. Also, in-situ characteristics of building elements could be adapted regarding environmental conditions with the aid of the AM process. Modified properties to control building physical properties and IEQ could be possible by varying densities due to compression and cavities. The possibility to integrate water based active systems such as thermoactive building systems have already been demonstrated [36]. In addition, also the relative humidity could be controlled which is depending on the supply temperature of the thermoactive building system below the dew point. Still, the influences in the change of the load-bearing behaviour regarding the water content has to be considered [113].

9. Question 9: In which way do digital fabricated building products from earth affect circularity?

On the one hand, digital fabrication of building products impacts on the extend of circularity through the input, consisting of choice of resource and the effort to process this into a material, the energy and emissions linked to the production process (e.g. extrusion, printing, ramming), and the amount of material needed to provide a function (material efficiency). On the other hand, circularity is affected by the output, which includes the post-use potential (or potential output), the effort for deconstruction (energy and emissions), and the reuse and recycling possibilities (resources) [41].

From a sustainable perspective, the traditional production of earth products shows many advantages. The requirement for digital manufacturing is to maintain these positive characteristics. Comparing the two processes, digital fabrication uses more energy and causes more emissions. However building products from automated techniques can use less material to provide high functionality [114]. Additionally, digital fabrication facilitates mono-material solutions for building components with increased performance demands like openings, whereby the use of (concrete) lintels can be waived [115].

Moreover, experiments from the Institute for Advanced Architecture of Catalonia (IAAC) have explored the possibilities of using the complex sections of additive manufactured earth walls to improve the thermal performance of walls by integrating natural ventilation. A prototype built in 2018 with controllable openings at the base and top of the wall allowed passive cooling based on convection during summer and heat storage during cold seasons by closing the openings. Furthermore, performance evaluations conducted by the IAAC have demonstrated that a significant thermal barrier effect can be realized by using site-specific designed surface geometries and wall sections based on a branching logic [116]. In return for these possibilities to minimize the required resources and operational energy use, additive manufacturing of clay walls is paired with increased requirements regarding the raw material. Compared to traditional techniques a higher moisture content is used for the additive manufacturing of clay to secure the extrudability of the clay during the printing process [117]. This increased water content results in a low strength of the wall until the clay is cured and a non-uniform shrinkage of the material. As the material shrinkage can have a drastic impact on the stability of the filigree wall section of additive manufactured walls, additives and aggregates are used to improve the material properties. It is of crucial importance for the circularity of the building whether the applied additives and aggregates are separable or harmless for the post-use of the material [6].

Schroeder distinguishes additives which only modify the physical properties of the earthen building materials without influencing the chemical structure of the clay minerals (e.g., straw) and additives that impact the chemical properties like cement or fly ash [6]. The first-mentioned are often used as reinforcement for additive manufactured clay walls in form of natural fibres. In addition, material studies of the IAAC document, that material shrinkage can be decreased by adding fibres like hemp, straw, or wood fibres [118]. Ongoing experiments at the Welsh School of Architecture (Cardiff University) investigate the possibilities of additively manufacturing earth walls without the use of chemical binders or liquefiers by only adding straw and silica sand [119].

Regarding circularity, a distinction must be made between additives that are primary raw material like jute and waste products such as rice husks. Clay building materials containing natural fibres can be mechanically separated if the clay is not contaminated through other additives or can be returned to the biological cycle after deconstruction. Nonetheless organic additives can lead to mould or sponge formation in the clay walls, thus recycling is no longer possible. Hydraulic binders like cement and hydraulic lime account as additives that impact the chemical structure. They are frequently used to increase the weather resistance of clay building materials. Since they cannot be sorted in the deconstruction process, high-quality recycling of the building material is not possible. In order to provide such opportunity, the non-earth components need to be separable and of a size that sorting machines can process.

10. Question 10: In which way does automated fabrication influence the characteristic design language of earthen construction?

Recent 1:1 scale experiments have shown that earthen materials can be formed using a variety of different digital fabrication techniques such as robotic fabrication and AM, including 3D printing through extrusion, robotic spraying, and robotic rammed earth [12]. The variety of prototypes showed that the shape of components is closely linked to the logic of their manufacturing process [64–66]. The shift in the manufacturing process to digital production changes the traditional requirements and offers a different design space for earthen buildings.

In an industrialised setting, the image of earthen materials is prevalently based on its ecologic benefits; formal or functional values tend to be neglected or reduced to the material's low-tech image. In our opinion, the introduction of digital fabrication techniques has helped to dismantle debatable perceptions regarding the contemporary use of earthen materials by emphasizing a rigorous, high-tech image by means of a precise formal architectural language resulting from the digital process.

Prefabrication is a commonly used technique for recently build rammed earth buildings, such as Herzog & de Meurons herb centre in Laufen, Switzerland [120]. Compared to prefabricated rammed earth elements, the formal language of robotically manufactured rammed earth is similar, differing only in its details, such as layer height and layer height-consistency. The characteristic appearance of a rammed earth wall is defined by horizontal lines, evidencing its layer wise build-up. These lines define the abrupt transition between the well compacted top region of the lower layer and the less compacted bottom region of the upper layer (Fig. 5). The robot-aided manufacturing of RE components allows reducing the layer height to a minimum, leading to vertically consistent compaction within one layer, which results in a reduced horizontal accentuation. We believe that the increased coherency of material parameters due to controllable compaction described in Q4 might lower safety factors for digitally manufactured rammed earth and consequently allow for more slender constructions in the future.

Spraying or printing earth significantly enlarges the design space of earthen constructions and paves the way for implementing a digital process chain. In order to allow for reciprocal influence, we suggest to link the production with the design process. Requirements of the manufacturing process should be incorporated in the design process, which avoids subsequent adaption and reworking. The direct transfer of information incorporated in a continuous digital process chain simplifies the precise execution of the 3D planned shapes. Subsequently, the way we build will change the formal language of earthen construction (see Fig. 1c).

Earth spraying, adapted from the SC3DP process (Q4) creates a rough surface and high layer bond due to high air pressure used to deploy the material. The surface finish of sprayed earth can be either left rough or treated directly after finishing of the spraying process to decrease surface roughness. The layer thickness can be controlled by the robot speed, whereas the layer width can be adjusted by varying the nozzle distance from the surface. Subtractive post processing offers the possibility to integrate precise joints and allows for precise reworking of the surfaces according to the desired finish.

Due to the thin strand width, the extrusion of soil offers the highest geometric resolution of the three described processes. In this process, high-resolution cavity wall elements can be produced, which gain stability not through their mass but through internal stiffening, similar to what is already known from concrete printing. Another similarity to concrete printing is the clear readability of the layers which are printed on top of each other. Layer thicknesses ranging from a few millimetres to several centimetres are possible.

Traditional earth building techniques offer countless geometric possibilities of shapes and surface finishes, which depend on the manufacturing process [11]. Each technique has its own advantages and restrictions defining specific design spaces. With the introduction of digital fabrication, new design spaces are added to earthen construction: In the case of 3D-printing, the possible combination of organic shapes and precision gained through the digitally controlled deposition of material can create novel, perceivable technical-organic formal orders (Fig. 1b and c).

Thus, potentials of automated manufacturing relate to an increased precision, manufacturing speed, consistency of mechanical properties and the possibility to create complex shapes. Consequently, components can be manufactured precisely according to physical, structural or aesthetical requirements. The interesting question of an appropriate architectural approach to incorporate these novel technologies on a building scale can only be answered by experiments and further investigations on a 1:1 scale of construction.

11. Conclusions

While earthen constructions are one of the oldest constructions by humans, the scientifically proven knowledge of this building technique varies with related aspects. On the one hand, the hygric capabilities, i.e. moist sorption and desorption of the material, are implemented in corresponding building standards (see Q1). On the other hand, the understanding of the hygro-thermal behaviour for example in relation to potentials in heat protection or dynamic thermal behaviour is very limited and requires substantial research. In the field of fire protection there is still great potential that has not yet been tapped due to a lack of research and development: Earth contains high amounts of crystal water, which is comparable to gypsum-based products, and could be used as fire protection for timber constructions. In the same line, satisfaction, well-being and health of the users in earthen buildings is often claimed as great advantage over other building materials, but scientific evidence is very limited and requires further research (Q8). In addition, advances in indoor-climatic simulations could lead to a reduction in ventilation and air-conditioning technology (Q2), and reduce life cycle costs (Q9). There is also a lack of methods to model the hygro-thermal behaviour of heterogeneous structures. This void reduces the potential to validate the empirically determined performance and also the

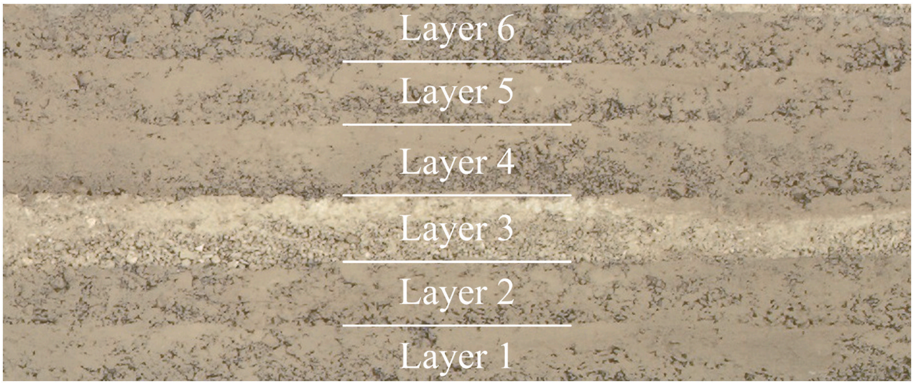

Fig. 5. Horizontal transition between traditionally manufactured rammed earth layers (©CLAYTEC Lehmbaustoffe).

implementation of design alternatives in performance evaluations. Overcoming these barriers are required to increase market shares. Hence, we argue that the information on the physical properties of products including earth needs to grow in order to become more easily integrated in any planning process.

At the same time, the potential of the earthen construction in light of timely discussions including climate change mitigation and adaptation measures is high. Firstly, earthen constructions have the potential to reduce or even replace technical building equipment; however, a proof-of-concept is still missing. Secondly, earth has many advantages within circular thinking, i.e. it can be reused endlessly in the life cycle or returned to nature at the possible end of live. However, such circulatory requires that earth is either left without any additives such as cement or only with carefully selected substances. Such note needs to be kept in mind when talking about new technologies within AM, which may require specific material properties and additives.

Up to today, there are few experiences with AM produced building elements made of earth and associated components. Most of these have to be regarded as prototypes. Examples worth to be mentioned are the partly automated prefabrication in the field of rammed earth construction, practiced in the Ricola Kräuterzentrum and the Alnatura Arbeitswelt [36]. Continuing developments in the automation of rammed earth technology may lead to greater process efficiencies and enable new design options in free forms. Further potentials for the design of solid earth walls can be seen in fused deposed modelling (FDM) technology: new combinations of different raw materials, if necessary additives and aggregates, and new spatial formations have a large potential for new wall systems. For example, air chambers could be arranged within the FDM process leading to different thermal resistance properties suitable for reducing heating energy losses. New surface designs can improve visual impression, acoustic and hygro-thermal properties of the wall element. Thereby, AM earth elements enable a construction that is precisely tailored to the IEQ requirements of different buildings or even different areas within buildings. The true potential lies in the connection with digital planning processes, which permit the customisation of elements and buildings and the direct implementation of these features at the construction side, while limiting requirements for artisanal work.

Despite all these potentials, limitations exist. One of them lies in the load-bearing capacities of earthen constructions. In Germany for example, buildings with only up to two storeys are permitted when constructed with solid earth. While this limitation has to be considered in the design phase, the connection to additively produced, optimized wooden structures or wooden skeleton structures offers a large potential. Through optimization of the statically necessary cross-section in combinations with new types of connections and automated production techniques in timber construction [121], earthen constructions can be introduced into multi-storey buildings. While the combination of wood and earth construction has been hand-made so far, additive manufacturing techniques may lead to complete prefabricated walls in the workshops, which saves time and construction costs.

Still, further development and research work is required to go beyond the scale of a prototype towards a wider implementation into the market. Such work needs to look at the potential of adapting the structural design to the functional requirements with regard to load-bearing behaviour, IEQ, well-being, and circularity. In addition, a strategy is needed for the transfer of the generated knowledge to actual building practice and the building industry. Such strategy needs to consider the existing lack of experience with the technologies, the lack of standards, and the necessity to create real-scale examples to increase trust and confidence in these technologies. In addition, effects on employment and know-how regarding traditional building techniques need to be considered. As digitally fabricated products are less labour-intensive, they might reduce employments. At the same time, increasing the market share of earthen products could potentially more than compensate for these losses.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

M.S. is supported by a research grant (21055) from VILLUM FONDEN.

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