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EARTH-BASED CONSTRUCTION: A CRITICAL REVIEW

BUDOWNICTWO ZIEMNE. KRYTYCZNY PRZEGLĄD LITERATURY

ABSTRACT

This paper presents a critical review of the literature on selected earth-based construction technologies published between January 2020 and July 2022 and indexed in Scopus. Publications on rammed earth, mudbricks and earth sheltering were reviewed and key research areas were identified, including, but not limited to the performance of unstabilized and stabilized earth partitions, the application of various stabilization materials, including waste, plant fibre and cement, characteristics of heritage earth structures, seismic vulnerability, life cycle analysis (LSA), and hygrothermal properties. It was concluded that a greater overlap between these areas could enhance the state of the art on earth-based technologies. Very little interest in earth shelters was observed, as the literature focused primarily on rammed earth and mudbrick.

Keywords: rammed earth, earth shelter, mudbrick, earth construction

STRESZCZENIE

Niniejszy artykuł przedstawia krytyczny przegląd literatury na temat wybranych technologii budowlanych opartych na ziemi opublikowanej między styczniem 2020 a lipcem 2022 roku, która została zaindeksowana w bazie Scopus. Zapoznano się z publikacjami dotyczącymi ziemi ubijanej w szalunkach, cegły suszonej i schronów ziemnych oraz zidentyfikowano kluczowe obszary badawcze, takie jak: efektywność stabilizowanych i niestabilizowanych przegród ziemnych, wykorzystanie różnorakich materiałów stabilizujących, w tym odpadów, włókien roślinnych oraz cementu, charakterystyka ziemnych obiektów zabytkowych, podatność na wstrząsy sejsmiczne, analiza cyklu życia (LCA) oraz właściwości hydrotermiczne. Stwierdzono, że większe przenikanie się obszarów badawczych mogłoby poszerzyć stan wiedzy na temat ziemnych technologii budowlanych. Zaobserwowano również nikłe zainteresowanie schronami ziemnymi, jako że literatura była skupiona głównie na ziemi ubijanej w szalunkach i na cegłach suszonych.

Słowa kluczowe: ziemia ubijana w szalunkach, schrony ziemne, cegła suszona, budownictwo ziemne

1. INTRODUCTION

Earth-based construction technologies have accompanied humanity since the beginning of civilization. Due to their low technological complexity and ease of use, they minimize the number of industrial processes necessary to produce building partitions, thus reducing embodied energy and emissions, as demonstrated by Pacheco-Torgal and Jalali (2012), who compared CO_2 emissions from mudbrick and rammed earth and with those of reference materials: fired brick and aerated concrete blocks. They found that the two earth-based materials yielded 22 and 26 kg CO_2/t, respectively, fired brick produced 200 kg CO_2/t, while aerated concrete blocks produced 375 kg CO_2/t. Earth-based construction materials are also attracting increasing interest from researchers who develop and advance them, extending their range of applications.

Sustainable development, as formulated by Brundtland (World Commission on Environment and

Development, 1987), can be seen as a broad goal, with numerous strategies that can be used to attain it. Two major and mutually opposing strategies of achieving it are green growth and de-growth (Sandberg, Klockars and Wilén, 2019). While the former employs technological advancement to reduce energy and material consumption and recycling while essentially keeping the amount of energy and resources in circulation at a given time quite high, the latter is about reducing the demand for them altogether while eschewing certain comforts and living standards. Earth-based construction technologies can be seen as fitting both approaches and thus as potential contributions to overall global sustainability. For instance, the Sirewall system employs carefully prepared, reinforced and stabilized rammed earth and was used to construct the tallest rammed earth structure to date — a telecommunications tower that is part of the Telenor Head Office complex in Islamabad, Pakistan, and stands 100 feet or around 30.5 m tall. Conversely, when not stabilized, earth can be used to construct buildings using pre-industrial tools and practically without electricity or fossil fuels, relying on careful design and material composition solutions — that require careful testing (Kelm and Długosz-Nowicka, 2011; Fabbri and Morel, 2019) — to increase its durability and strength (Minke, 2012).

Earth-based materials were also found to perform well in sustainability-focused building life-cycle analysis (LCA), with promising results for sun-dried bricks versus fired clay bricks presented by Dabaieh et al. (2020). A holistic analysis by Ben-Alon et al. (2021) also supported the use of natural materials in construction, earth included, in an LCA comparative study of natural and conventional building materials, showing that straw clay and insulated rammed earth outperformed all other materials for all the six climates they analysed. The large-scale application potential of rammed earth and mudbrick was also explored, indicating varying potential for emissions and embodied energy reduction depending on the desired technological and material uniformity which may affect building functional performance and design potential due to limiting the usable palette of structural solutions (Barnaś, 2021, p. 147). One of the major advantages of using earth-based technologies is their local availability, which significantly cuts down on emissions and energy consumption associated with transport, as observed by Arrigoni et al. (2018), who came to this conclusion in their investigation of the use of recycled concrete aggregate as an additive to rammed earth. Unstabilized rammed earth was also given an A+ rating when used for external walls in commercial buildings in the BRE 2008 Green Guide used in BREEAM certification (BRE, 2008).

This paper presents the results of an integrative literature review intended to identify, examine and present key developments in research on selected earth-based construction technologies and chart potential avenues for future investigation (Torraco, 2005) as based on relevance measured by citation numbers.

Goal of the paper

The goal of this study was to examine the latest developments in research on selected earth-based construction technologies, specifically rammed earth, mudbrick and earth sheltering, with a focus on how these technologies may aid in attaining sustainability, and to identify major themes, research trajectories and knowledge gaps for future investigation.

Methods

This review was performed following the methodology used previously by Radziszewska-Zielina et al. (2022) to review the literature on brownfield adaptive reuse projects, following general review guidelines by Snyder (2019). This methodology features the use of an internationally recognized and searchable reference indexing database — Scopus — to search for articles using a preselected set of keywords and confining the results to a specific date range. In this study, the Scopus search engine was used to search for the keywords ‘rammed earth’, ‘adobe’, ‘mudbrick’, ‘mud brick’ and ‘earth shelter’ and the resulting articles were screened for compliance with the investigation’s subject. Unrelated articles were removed from the pool. The remaining articles were then sorted by relevance measured by the number of citations and arranged into thematic categories and their major findings were discussed, with key themes and research trajectories identified and presented (ill. 1).

Scope

The aim of the study was to present the latest in earth-construction-focused and associated sustainability research. Therefore, the literature search was limited to research and review articles published between January 2020 and July 2022 — which corresponded to a date range of 2020 and 2022, July being the month the study was performed — and were indexed in the Scopus reference database. The thematic scope included all matters that could potentially relate to earth-based construction and its application in achieving sustainability, especially

sustainable cities, including, but not limited to, materials science, architecture, civil engineering, urban planning and chemistry. To gauge interest among researchers, the number of articles published in the years 2000–2022 (July) was also examined, along with their relevance, as measured by the number of citations, while articles from before 2020 were not reviewed per se. The articles were not divided by place of publication. The literature reviewed was not sorted by applicability to specific climate zones.

Literature review

As this study is in itself a literature review, it has been presented further in the paper. Similar reviews to this one were presented by, among others, Medvey and Dobszay (2020) and Ghasemalizadeh and Toufigh (2020). However, they were mostly focused on singular technologies, such as stabilized rammed earth, to the exclusion of other materials such as adobe. Gomaa et al. (2022) presented a review focused on digital manufacturing techniques for earth construction, while Venkatarama Reddy et al. (2022) investigated relevant legal codes and standards applicable to the field. A material-focused review of literature on fibre-reinforced adobe was conducted by Salih, Osofero and Imbabi (2020), with a similar review presented by Ramakrishnan et al. (2020).

Recent reviews were found to be highly specialized, namely focusing only on singular aspects of a given material or its application. An absence of more generalized reviews that would assess the field of earth construction as a whole was found. Likewise, there appeared to be no recent reviews that compared research on multiple earth-based technologies. These are gaps this review was aimed to address.

2. RESULTS

Interest trends (2000–2022)

The Scopus referencing database search engine was used to search for the keywords specified in the previous section, returning a total of 7,075 document results, with publications dated between 1868 and 2023. To gauge trends in interest in the subject under investigation, the search results were limited to the period between the year 2000 and July 2022. The total number of articles published during this period and indexed in Scopus was 6,646. The number of articles published in each year has been presented in illustration 2.

A steady, overall rise in the number of publications on the subject under study during the period was observed, with the lowest number being 65 articles published and indexed in 2000, and the highest being 536, indexed in 2021, which is also the all-time highest number. A relatively steady rise in articles published could be observed throughout the period, with a significant spike (486) recorded in 2012. The average number of articles published in the last five full years (2017–2021) was 441 articles per year. The number for the first seven months of 2022 was 287, which means that the positive trend can be expected to continue.

The latest literature (January 2020 — June 2022): number of publications

A total of 1,332 articles were published in the period under investigation. When sorted by subject area, the highest number of articles was published in Engineering (478), with other subject areas with more than 200 articles published being Computer Science (248), the Social Sciences (222), Materials Science (218) and Medicine (205). As this study focused primarily on sustainability, articles in the field of Medicine and related fields were not investigated in detail.

It was observed that the use of the keyword ‘adobe’ produced unwanted results related to Adobe Inc. and broadly understood image processing, which skewed the results towards unrelated Computer Science articles. However, removing ‘adobe’ from the search resulted in a drastic drop of document results down to 374 documents, leading to the removal of articles that referred to mudbrick exclusively using the term in questions. This was deemed inadmissible in the light of the term’s popularity. Likewise, filtering out subject areas using the search engine’s functionally could potentially eliminate key multidisciplinary studies such as that of Anysz et al. (2020), which explored the application of explainable artificial intelligence in assessing the compressive strength of rammed earth components, and thus leaned very heavily into Computer Science. As the problem presented could potentially render some of this study’s results unreliable, the articles were manually screened for concordance with the review’s main theme, and therefore any interpretation of this study’s quantitative results should factor in this caveat and their use as an initial tool.

Relevance, most-cited articles

In terms of relevance as measured by the number of citations, the article with the highest number of citations from a non-medical field was a study by Gu and Chen (2020), who investigated the addition of cement, waste phosphogypsum, fly ash and

quicklime as applied to rammed earth, reaching 84 citations as of the writing of this paper. The article with the second-highest number of citations (29), by Li Piani et al. (2020), discussed the dynamic behaviour of adobe bricks in compression and how fibres and water content affected this behaviour. The vast majority of articles were cited less than 20 times, with only 9 articles having citations within the 20–29 range as of the writing of this study. These articles mostly explored sustainability-related aspects such as the addition of various wastes such as tire fibres (Zare et al., 2020) or paper and pulp (Muñoz et al., 2020), mixing in plant materials (Olacia et al., 2020) into adobe brick, as well as providing an overall characterization of rammed earth's mechanical and physical properties (Ávila, Puertas and Gallego, 2021). A study on the seismic vulnerability of adobe housing and the reduction of this vulnerability (Preciado et al., 2020) and the previously mentioned article by Anysz et al. were clear thematic outliers in this group.

Articles with citations in the 10–19 range were much more numerous (37) and focused on a greater variety of subjects. The first was decision-making support tools, specifically in the architectural conservation of the Ming Great Wall, and the application of MCDA (multi-criteria decision analysis) methods in this process (Du et al., 2020), or the development of a decision tool for soil suitability in using earth-based technologies for construction (Rojat et al., 2020). The second distinctive subject was damage to earthen structures, i.e., caused by wind-driven rain (Luo et al., 2020), or methods of repairing it in a conservation context using microbially induced carbonate precipitation (Liu et al., 2020). One interesting outlier was an exploration of the use of earth as a construction material in a circular economy, as proposed by Morel et al. (2021).

A substantial number of studies in this group concerned heritage sites, apart from the above-mentioned studies by Du et al. (2020) and Liu et al. (2020), there were also general studies where earthen materials were one of the components under study, such as in the article by Fierascu, Doni and Fierascu (2020), which explored historical wooden and masonry buildings, and by Zhao et al. (2020), which investigated a range of heritage sites in China in terms of their thermal environments. Another interesting study was presented by Sumerente et al. (2020), who analysed the seismic performance of buildings in the Peruvian Andes by simulating their behaviour using Monte Carlo simulation and a Probability Damage Matrix. Most other articles continued the major research trajectories from the group with citation numbers within the 20–29 range, especially investigating various admixtures that can be used to stabilize earthen materials, including plant fibres (Ige and Danso, 2021), and soil mineral compositions on mechanical properties (Narloch et al., 2020).

It should be noted that out of all the articles found, only 1 discussed earth shelters, and indirectly so, as it concerned primarily excavation techniques and architecture carved from rock in Iran (Mangeli et al., 2022). Rock shelters are a subset of earth shelters and due to differences in material, cannot be justifiably equated with traditional earth shelters in which a building's envelope, which can be constructed of any material, is covered with soil.

Major research directions

When investigated from a perspective of identifying major research trajectories, the literature could be divided into the following categories:

- Performance of unstabilized (earth-only) materials and technologies, involving compressive strength and durability testing;
- Effects of adding stabilizers to earth-based materials, in the form of cement, plant fibres or waste products;
- Seismic vulnerability of adobe and rammed earth buildings;
- Material characterizations of heritage buildings in a given region;
- Life cycle analyses and comparative studies;
- Thermal characteristics evaluations.

A summary of the research directions identified over the course of the review, along with sample studies for each direction, has been presented in Table 1.

The literature on earth shelters, due to the minuscule number of studies, was not factored into the analysis.

Direction	Citation	Problem	Findings summary
Performance of unstabilized materials	Traoré et al., 2021	freezing-thawing resistance of rammed earth	cement-stabilized earth found to have greater frost and scaling resistance
	Mirjalili, Eslami and Morshed, 2020	effect of vertical loading on in-plane cyclic behaviour of adobe walls	precompression increases in-plane lateral resistance of walls, lateral stiffness is enhanced as vertical precompression increases
Performance of stabilized materials, stabilization materials	Shrestha et al., 2020	simple ways of strengthening rammed earth structures	major causes of failure of rammed earth structures analysed, reinforcement using wooden dowels was proposed and tested
	Pavan, Ullas and Nanjunda Rao, (2020)	shear behaviour of cement-stabilized rammed earth	three types of CSRE (cement stabilized rammed earth) bonding tested, specimen with cement slurry at interface displayed highest shear strength
	Meybodian, Eslami and Morshed, 2020	natural reinforcements in traditional adobe walls	palm mesh, plastic mesh, palm rope and reed reinforcements tested, EB palm meshes with rhombus arrangement and diagonal NSM reeds found to be the strongest
	Losini et al., 2021	natural additives and biopolymers as stabilizers reviewed	lack of management of new waste and by-products a major issue, biopolymers show promise as they enhance ductility, plasticity, viscosity and cohesion
	Abdulla, Cunningham and Gillie, 2020	mechanical properties of straw fibre-reinforced adobe masonry	precompression plays significant role in avoiding cracking under load, unit-to-mortar interface showed lower tensile strength to the masonry unit itself
Seismic vulnerability	Bui et al., 2020	out-of-plane behaviour of rammed earth walls under seismic loading simulated using the finite element method	concrete bond beams can prevent overturning modes and reduce out-of-plane drift
	Li, Noori and Altabey, 2021	assessment of seismic performance of adobe walls	bottom walls found to be prone to shear failure; wall acceleration response and lack of synchronization found to be main failure factor
	Khan, Ahmad and Ahmad, 2021	confined adobe masonry structures tested for seismic vulnerability using a shake table	use of vertical columns significantly improved test performance
	Brando et al., 2021	vulnerability assessment of historical dwellings in Cusco, Peru	seismic vulnerability assessment model implemented, and vulnerability curves calculated, proposal of large-scale preventative retrofits

Direction	Citation	Problem	Findings summary
Material characterizations of heritage buildings	Jiang et al., 2020	hygrothermal performance of rammed earth in the Tibetan Autonomous Prefecture, China	no differences in hygrothermal properties in relation to other studies, with lower overall water vapour permeability, better temperature buffering, thermal stability and moisture buffering
	Luo et al., 2021	rammed earth degradation under soluble salts attack	mixed salt with Na_2SO_4:$CaCl_2$ at a 1:1 ratio caused a sharp drop in strength, high degree of salinity considerably worsened shear stress test performance
	Parracha et al. (2020)	characterization of rammed earth in a 12th-century castle in Portugal	so-called 'military' rammed earth — stabilized with lime — found, mineralogical analysis presented
Life cycle analyses	Meek et al., 2021	recycled waste and industrial by-products as stabilizers in rammed earth	adopting alkali-activated rammed earth envelopes in new residential buildings can provide 1.2–1.3% of the greenhouse gas emission reductions set by Australia's Paris Agreement target by 2030
Hygrothermal characteristics	Samadianfard and Toufigh, 2020	energy use and thermal performance in rammed earth	acrylic insulator found to enhance rammed earth thermal characteristics
	Saboor et al., 2021	wall envelope design to reduce air-conditioning costs	wall envelope designs for fired brick, mudbrick, laterite stone and cinder concrete proposed, and air-conditioning costs and payback times calculated

Tab. 1. Major research directions identified in the review with sample articles. By the author.

Tab. 1. Główne kierunki badań zidentyfikowane w trakcie przeglądu literatury z przykładowymi artykułami. Opracowanie własne.

3. DISCUSSION AND CONCLUSIONS

Future research trajectories

The literature review presented in this paper yielded a number of interesting insights into the state of the art on earth construction technologies. The first is that it is predominated by research on rammed earth and adobe buildings, and that studies into the mechanical properties of these materials and means of enhancing them via stabilization are the most numerous and most cited. Specifically, investigations of various stabilizers appear to be promising. From a sustainability standpoint, the potential application of recycled materials and plant matter in this role should be pursued further, with studies into the use of cement itself appearing to reach a robust knowledge base. In terms of life cycle analysis, there appears to be little room for major improvements, as the benefits of the use of earth-based materials have been explored quite thoroughly. Future research in this direction could tie in with studies on the use of waste products as stabilizers and the broader impact this could have on waste management, recycling and reuse, providing more global insights.

Investigations of heritage sites featuring earthen architecture should continue, with an emphasis on historical construction techniques, material compositions and characteristics, as well as their possible contemporary application. As the amount of such architecture is quite substantial, researchers will find no shortage of research material. Seismic vulnerability ties into this, as it is vital to the preservation of built heritage in areas endangered by earthquakes and the durability of contemporary structural systems. Efforts can be directed towards cataloguing and surveying the existing condition of heritage sites whose protection against earthquakes is deemed unfeasible. Another potential avenue may be the analysis of potential new uses for earthen heritage buildings, which could be supplemented by suitable methods (Śladowski et al., 2021). Research into hygrothermal characteristics could follow a similar direction to life cycle analysis

studies, namely focus more on the impact of stabilizers on material behaviour, or to identifying design solutions that minimize the need for highly processed construction materials and products, facilitating the retention of comfort of use while doing so.

In comparison to previous reviews, specifically those outlined in the introduction, a notable lack of overlap between subfields was observed, which can be seen as a deficiency that needs addressing. This also applies to research articles. Similarly, research that would compare advances in each earth-based construction technology was found to be scant. As other recent reviews were not as wide-ranging, it can be argued their results are difficult to compare due to their fundamentally different scopes.

The near-absence of research into earth-sheltered architecture is worth noting and is troubling. What little research on this subject that was found focused on historical buildings and it appears this approach was not being developed further for contemporary use.

Limitations

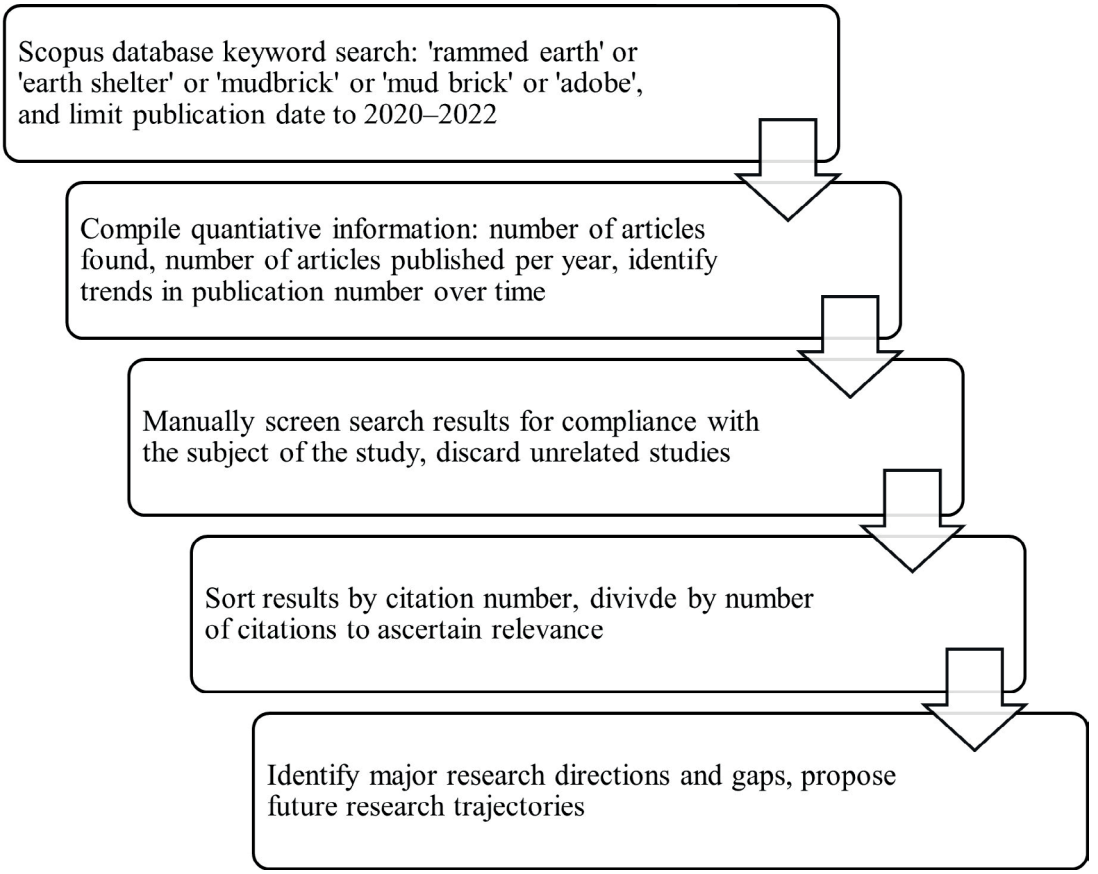
This study suffered from a range of limitations mostly inherent to its design as based on the Scopus database search engine. The first and most notable limitation is that it was difficult to ascertain the exact number of relevant publications based on a keyword search alone. A detailed analysis of the literature was necessary to filter out the number of studies that were outside of the field under investigation. This is crucial, as the initial search results included a high number of publications that were clearly focused on medicine and image processing, possibly constituting around a tenth of the overall results and thus potentially skewing the reported number of studies. A more comprehensive, custom tool to process initial search results could be used to address this issue. However, despite this deficiency, the overall value of the study was not lowered, as the main aim of the investigation and review — determining major research directions and future trajectories of investigation — could be performed without it.

Closing remarks

This review presented a concise overview of a section of crucial literature on rammed earth and adobe construction technologies, which are valuable tools that can be used to attain sustainability regardless of the adopted strategy of reaching it. The primary conclusion that can be drawn from the review is that future studies should place a greater emphasis on increasing the overlap between current research directions, especially when it comes to investigating the role of stabilizing materials in rammed earth and adobe structures and their impact on structural and hygrothermal performance, as especially this last subject is currently not documented very well in the literature. In addition, a more global outlook is needed in life cycle analyses, bringing to light the potential role that earth-based materials can play in large-scale sustainability efforts and how they can tie in with other measures such as waste management. This necessitates an extension of LCA methodologies.

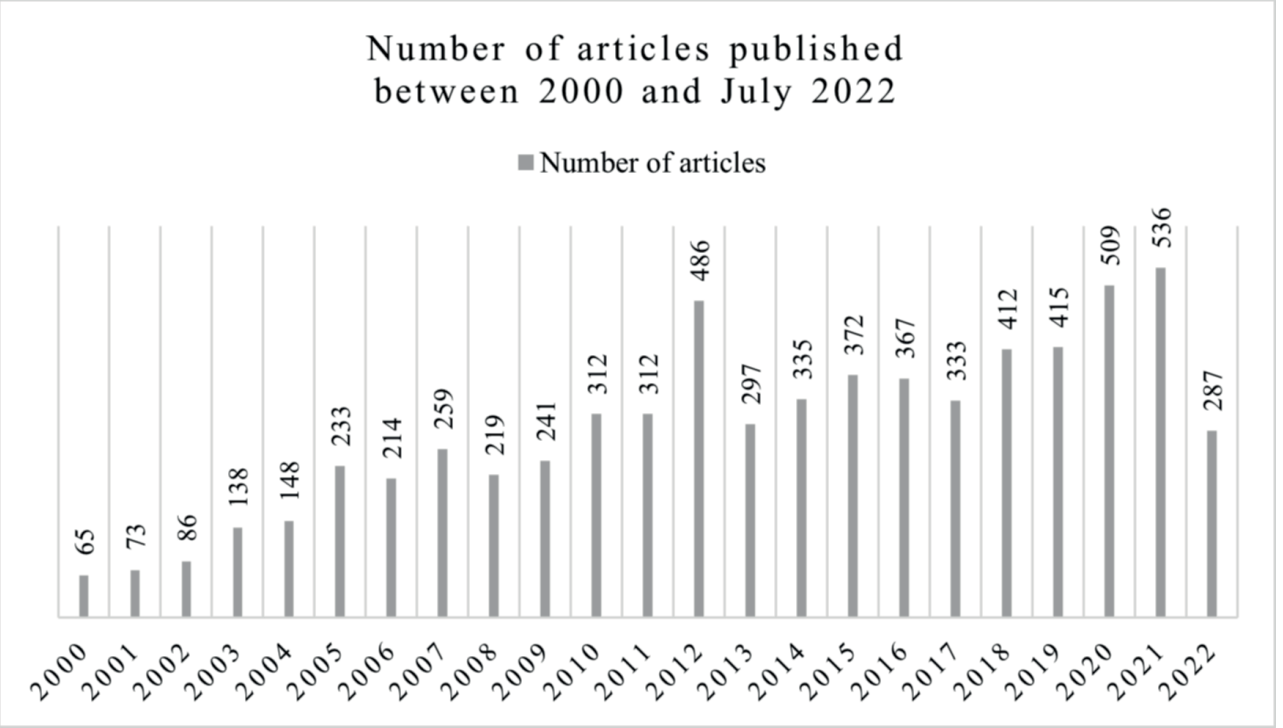
Future efforts in continuing the literature analysis presented here should expand beyond the Scopus search engine and aim to develop more accurate means of filtering relevant publications for the collection of quantitative data.

The findings of this review can be universally applied in research on earth-based construction, especially as they concern a large part of the field as a whole and not its specific subfields, understood as aspects of a specific technology — contrary to other recent reviews. Due to this trait alone, this study fills the stated research gap of an absence of wide-scope reviews of the most recent literature on earth-based construction.



Ill. 1. Methodology scheme used in this study. By the author.

Il. 1. Schemat metodologiczny niniejszego badania. Opracowanie własne.



Ill. 2. Number of articles featuring the keywords ‘rammed earth’, ‘earth shelter’, ‘adobe’, ‘mudbrick’ and ‘mud brick’ published between 2000 and July 2022. By the author.

Il. 2. Liczba artykułów zawierających słowa kluczowe: „ziemia ubijana”, „schron ziemny”, „cegła ziemna” oraz „adobe”, opublikowanych między rokiem 2000 a lipcem 2022. Opracowanie własne.

REFERENCES

Abdulla, K.F., Cunningham, L.S. and Gillie, M. (2020), 'Experimental Study on the Mechanical Properties of Straw Fiber-Reinforced Adobe Masonry,' *Journal of Materials in Civil Engineering*, 32(11), 04020322. Available at: http://dx.doi.org/10.1061/(ASCE)MT.1943-5533.0003410 (accessed: 16.07.2022).

Anysz, H. et al. (2020). 'Feature Importance of Stabilised Rammed Earth Components Affecting the Compressive Strength Calculated with Explainable Artificial Intelligence Tools,' *Materials*, 13(10), 2317. Available at: https://doi.org/10.3390/ma13102317 (accessed: 16.07.2022).

Arrigoni, A. et al. (2018), 'Rammed Earth Incorporating Recycled Concrete Aggregate: A Sustainable, Resistant and Breathable Construction Solution,' *Resources, Conservation and Recycling*, 137, pp. 11–20. Available at: https://doi.org/10.1016/j.resconrec.2018.05.025 (accessed: 16.07.2022).

Ávila, F., Puertas, E. and Gallego, R. (2021), 'Characterization of the Mechanical and Physical Properties of Unstabilized Rammed Earth: A Review', *Construction and Building Materials*, 270, 121435. Available at: https://doi.org/10.1016/j.conbuildmat.2020.121435 (accessed: 16.07.2022).

Barnaś, K. (2021), *Technologia surowej ziemi w projektowaniu urbanistyczno-architektonicznym*, PhD thesis, Cracow University of Technology.

Ben-Alon, L. et al. (2021), 'Life Cycle Assessment (LCA) of Natural vs Conventional Building Assemblies,' *Renewable and Sustainable Energy Reviews*, 144, 110951. Available at: https://doi.org/10.1016/j.rser.2021.110951 (accessed: 16.07.2022).

Brando, G. et al. (2021), 'Structural Survey and Empirical Seismic Vulnerability Assessment of Dwellings in the Historical Centre of Cusco, Peru,' *International Journal of Architectural Heritage*, 15(10), pp. 1395–1423. Available at: http://dx.doi.org/10.1080/15583058.2019.1685022 (accessed: 16.07.2022).

BRE (2008), 'Green Guide 2008 Ratings,' *BREGroup.com*. Available at: https://tools.bregroup.com/greenguide/ggelement.jsp?buildingType=Offices&category=1019&parent=6&elementType=10166 (accessed: 9.09.2022).

Bui, T.L. et al. (2020), 'Out-of-Plane Behavior of Rammed Earth Walls Under Seismic Loading: Finite Element Simulation,' *Structures*, 24, pp. 191–208. Available at: https://doi.org/10.1016/j.istruc.2020.01.009 (accessed: 16.07.2022).

Dabaieh, M. et al. (2020), 'A Comparative Study of Life Cycle Carbon Emissions and Embodied Energy Between Sun-Dried Bricks and Fired Clay Bricks,' *Journal of Cleaner Production*, 275, 122998. Available at: https://doi.org/10.1016/j.jclepro.2020.122998 (accessed: 16.07.2022).

Du, Y. et al. (2020), 'Study on Damage Assessment of Earthen Sites of the Ming Great Wall in Qinghai Province Based on Fuzzy-AHP and AHPT-TOPSIS,' *International Journal of Architectural Heritage. Conservation, Analysis, and Restoration*, 14(6), pp. 903–916. Available at: https://doi.org/10.1080/15583058.2019.1576241 (accessed: 16.07.2022).

Fabbri, A. and Morel J.C. (2019), 'The Performance Testing of Earthen Materials: Challenges and Future Developments,' [in:] Ganjian, E. et al. (eds.), *Proceedings of Fifth International Conference on Sustainable Construction Materials and Technologies (SCMT5): In Honour of The International Union of Laboratories and Experts in Construction Materials, Systems and Structures (RILEM)*, Coventry: Coventry University. Available at: http://dx.doi.org/10.18552/2019/IDSCMT5190 (accessed: 16.07.2022).

Fierascu, R.C., Doni, M. and Fierascu, I. (2020), 'Selected Aspects Regarding the Restoration/Conservation of Traditional Wood and Masonry Building Materials: A Short Overview of the Last Decade Findings,' *Applied Avail-able* , 10(3), 1164. Available at: https://doi.org/10.3390/app10031164 (accessed: 16.07.2022).

Ghasemalizadeh, S. and Toufigh, V. (2020), 'Durability of Rammed Earth Materials', *International Journal of Geomechanics*, 20(11), 04020201. Available at: http://dx.doi.org/10.1061/(ASCE)GM.1943-5622.0001829 (accessed: 16.07.2022).

Gomaa, M. et al. (2022), 'Digital Manufacturing for Earth Construction: A Critical Review,' *Journal of Cleaner Production*, 388, 130630. Available at: https://doi.org/10.1016/j.jclepro.2022.130630 (accessed: 16.07.2022).

Gu, K. and Chen, B. (2020), 'Loess Stabilization Using Cement, Waste Phosphogypsum, Fly Ash and Quicklime for Self-Compacting Rammed Earth Construction,' *Construction and Building Materials*, 231, 117195. Available at: https://doi.org/10.1016/j.conbuildmat.2019.117195 (accessed: 16.07.2022).

Ige, O. and Danso, H. (2021), 'Physico-Mechanical and Thermal Gravimetric Analysis of Adobe Masonry Units Reinforced with Plantain Pseudo-Stem Fibres for Sustainable Construction,' *Construction and Building Materials*, 273, 121686. Available at: https://doi.org/10.1016/j.conbuildmat.2020.121686 (accessed: 16.07.2022).

Jiang, B. et al. (2020), 'Hygrothermal Performance of Rammed Earth Wall in Tibetan Autonomous Prefecture in Sichuan Province of China,' *Building and Environment*, 181, 107128. Available at: https://doi.org/10.1016/j.buildenv.2020.107128 (accessed: 16.07.2022).

Kelm, T. and Długosz-Nowicka, D. (2011), *Budownictwo z surowej ziemi. Idea i realizacja*, Warszawa: Oficyna Wydawnicza Politechniki Warszawskiej.

Khan, F.Z., Ahmad, M.E. and Ahmad, N. (2021), 'Shake Table Testing of Confined Adobe Masonry Structures,' *Earthquakes and Structures*, 20(2), pp. 149–160. Available at: http://dx.doi.org/10.12989/eas.2021.20.2.149 (accessed: 16.07.2022).

Li, Z., Noori, M. and Altabey, W.A. (2021), 'Experimental and Numerical Assessment on Seismic Performance of Earth Adobe Walls,' *SDHM Structural Durability and Health Monitoring*, 15(2), pp. 103–123. Available at: http://dx.doi.org/10.32604/sdhm.2021.011193 (accessed: 16.07.2022).

Li Piani, T. et al. (2020), 'Dynamic Behaviour of Adobe Bricks in Compression: The Role of Fibres and Water Content at Various Loading Rates,' *Construction and Building Materials*, 230, 117038. Available at: https://doi.org/10.1016/j.conbuildmat.2019.117038 (accessed: 16.07.2022).

Liu, S. et al. (2020), 'Preliminary Study on Repairing Tabia Cracks by using Microbially Induced Carbonate Precipitation,' *Construction and Building Materials*, 248, 118611. Available at: https://doi.org/10.1016/j.conbuildmat.2020.118611 (accessed: 16.07.2022).

Losini, A.E. et al. (2021), 'Natural Additives and Biopolymers for Raw Earth Construction Stabilization — A Review,' *Construction and Building Materials*, 304, 124507. Available at: https://doi.org/10.1016/j.conbuildmat.2021.124507 (accessed: 16.07.2022).

Luo, Y. et al. (2020), 'Degradation of Rammed Earth Under Wind-Driven Rain: The Case of Fujian Tulou, China,' *Construction and Building Materials*, 261, 119989. Available at: https://doi.org/10.1016/j.conbuildmat.2020.119989 (accessed: 16.07.2022).

Luo, Y. et al. (2021), 'Degradation of Rammed Earth Under Soluble Salts Attack And Drying-Wetting Cycles: The Case of Fujian Tulou, China,' *Applied Clay Science*, 212, 106202. Available at: https://doi.org/10.1016/j.clay.2021.106202 (accessed: 16.07.2022).

Mangeli, M. et al. (2022), 'A New Look at Excavation Techniques and Design of Rock-Cut Architectures,' *Designs*, 6(4), 64. Available at: https://doi.org/10.3390/designs6040064 (accessed: 16.07.2022).

Medvey, B. and Dobszay, G. (2020), 'Durability of Stabilized Earthen Constructions: A Review,' *Geotechnical and Geological Engineering*, 38, pp. 2403–2425. Available at: https://doi.org/10.1007/s10706-020-01208-6 (accessed: 16.07.2022).

Meek, A.H. et al. (2021), 'Alternative Stabilized Rammed Earth Materials Incorporating Recycled Waste and Industrial By-Products: Life Cycle Assessment,' *Construction and Building Materials*, 267, 120997. Available at: https://doi.org/10.1016/j.conbuildmat.2020.120997 (accessed: 16.07.2022).

Meybodian, H., Eslami, A. and Morshed, R. (2020), 'Sustainable Lateral Strengthening of Traditional Adobe Walls Using Natural Reinforcements,' *Construction and Building Materials*, 260, 119892. Available at: https://doi.org/10.1016/j.conbuildmat.2020.119892 (accessed: 16.07.2022).

Minke, G. (2012), *Building with Earth: Design and Technology of a Sustainable Architecture*, Basel: Birkhäuser Verlag.

Mirjalili, A., Eslami, A. and Morshed, R. (2020), 'Experimental Investigation into the Effect of Vertical Loading on In-Plane Cyclic Behavior of Adobe Walls,' *Construction and Building Materials*, 264, 120706. Available at: https://doi.org/10.1016/j.conbuildmat.2020.120706 (accessed: 16.07.2022).

Morel, J.C. et al. (2021), 'Earth as Construction Material in the Circular Economy Context: Practitioner Perspectives on Barriers to Overcome,' *Philosophical Transactions of the Royal Society B: Biological Sciences*, 376(1834). Available at: https://doi.org/10.1098/rstb.2020.0182 (accessed: 16.07.2022).

Muñoz, P. et al. (2020), 'Adobe Bricks Reinforced with Paper & Pulp Wastes Improving Thermal and Mechanical Properties,' *Construction and Building Materials*, 254, 119314. Available at: https://doi.org/10.1016/j.conbuildmat.2020.119314 (accessed: 16.07.2022).

Narloch, P. et al. (2020), 'The Effect of Soil Mineral Composition on the Compressive Strength of Cement Stabilized Rammed Earth,' *Materials*, 13(2), 324. Available at: https://doi.org/10.3390%2Fma13020324 (accessed: 16.07.2022).

Olacia, E. et al. (2020), 'Sustainable Adobe Bricks with Seagrass Fibres. Mechanical and Thermal Properties Characterization,' *Construction and Building Materials*, 239, 117669. Available at: https://doi.org/10.1016/j.conbuildmat.2019.117669 (accessed: 16.07.2022).

Pacheco-Torgal, F. and Jalali, S. (2012), 'Earth Construction: Lessons from the Past for Future Eco-Efficient Construction', *Construction and Building Materials*, 29, pp. 512–519. Available at: https://doi.org/10.1016/j.conbuildmat.2011.10.054 (accessed: 16.07.2022).

Parracha, J.L. et al. (2020), 'Mineralogical and Microstructural Characterisation of Rammed Earth and Earthen Mortars from 12th Century Paderne Castle,' *Journal of Cultural Heritage*, 42, pp. 226–239. Available at: https://doi.org/10.1016/j.culher.2019.07.021 (accessed: 16.07.2022).

Pavan, G.S., Ullas, S.N. and Nanjunda Rao, K.S. (2020), 'Shear Behavior of Cement Stabilized Rammed Earth Assemblages,' *Journal of Building Engineering*, 27, 100966.

Preciado, A. et al. (2020), 'Seismic Vulnerability Assessment and Reduction at a Territorial Scale on Masonry and Adobe Housing by Rapid Vulnerability Indicators: The Case of Tlajomulco, Mexico,' *International Journal of Disaster Risk Reduction*, 44, 101425.

Radziszewska-Zielina, E. et al. (2022), 'Decision-Making Support for Housing Projects in Post-Industrial Areas,' *Sustainability*, 14(6), 3573. Available at: https://www.mdpi.com/2071-1050/14/6/3573, https://doi.org/10.3390/su14063573 (accessed 10.07.2022).

Ramakrishnan, S. et al. (2020), 'Adobe Blocks Reinforced with Natural Fibres: A Review,' *Materials Today: Proceedings*, 45(7), pp. 6493–6499. Available at: https://www.sciencedirect.com/science/article/pii/S2214785320389951 (accessed: 16.07.2022).

Rojat, F. et al. (2020), 'Towards an Easy Decision Tool to Assess Soil Suitability for Earth Building,' *Construction and Building Materials*, 257, 119544. Available at: https://doi.org/10.1016/j.conbuildmat.2020.119544 (accessed: 16.07.2022).

Saboor, S. et al. (2021), 'Strategic Design of Wall Envelopes for the Enhancement of Building Thermal Performance at Reduced Air-Conditioning Costs,' *Environmental Research*, 193, 110577. Available at: https://doi.org/10.1016/j.envres.2020.110577 (accessed: 16.07.2022).

Salih, M.M., Osofero, A.I. and Imbabi, M.S. (2020), 'Critical Review of Recent Development in Fiber Reinforced Adobe Bricks for Sustainable Construction,' *Frontiers of Structural and Civil Engineering*, 14(4), pp. 839–854.

Available at: https://doi.org/10.1007/s11709-020-0630-7 (accessed: 16.07.2022).

Samadianfard, S. and Toufigh, V. (2020), 'Energy Use and Thermal Performance of Rammed-Earth Materials,' *Journal of Materials in Civil Engineering*, 32(10), 04020276. Available at: https://ascelibrary.org/doi/pdf/10.1061/%28ASCE%29MT.1943-5533.0003364?download=true (accessed: 16.07.2022).

Sandberg, M., Klockars, K. and Wilén, K. (2019), 'Green Growth or Degrowth? Assessing the Normative Justifications for Environmental Sustainability and Economic Growth Through Critical Social Theory,' *Journal of Cleaner Production*, 206, pp. 133–141. Available at: https://doi.org/10.1016/j.jclepro.2018.09.175 (accessed: 16.07.2022).

Shrestha, K.C. et al. (2020), 'Strengthening of Rammed Earth Structures with Simple Interventions,' *Journal of Building Engineering*, 29, 101179. Available at: https://doi.org/10.1016/j.jobe.2020.101179 (accessed: 16.07.2022).

Snyder, H. (2019), 'Literature Review as a Research Methodology: An Overview and Guidelines,' *Journal of Business Research*, 104, pp. 333–339. Available at: https://doi.org/10.1016/j.jbusres.2019.07.039 (accessed: 16.07.2022).

Sumerente, G. et al. (2020), 'Assessment of Combined In-Plane and Out-of-Plane Fragility Functions for Adobe Masonry Buildings in the Peruvian Andes,' *Frontiers in Built Environment*, 6, 52. Available at: https://www.frontiersin.org/articles/10.3389/fbuil.2020.00052/full (accessed: 16.07.2022).

Śladowski, G. et al. (2021), 'The Boyen Fortress: Structural Analysis of Selecting Complementary Forms of Use for a Proposed Adaptive Reuse Project,' *Heritage Science*, 9, 76. Available at: https://doi.org/10.1186/s40494-021-00550-z (accessed: 16.07.2022).

Torraco, R.J. (2005), 'Writing Integrative Literature Reviews: Guidelines and Examples,' *Human Resource Development Review*, 4(3), pp. 356–367. Available at: https://doi.org/10.1177/1534484305278283 (accessed: 16.07.2022).

Traoré, L.B. et al. (2021), 'Experimental Assessment of Freezing-Thawing Resistance of Rammed Earth Buildings,' *Construction and Building Materials*, 274, 121917. Available at: https://doi.org/10.1016/j.conbuildmat.2020.121917 (accessed: 16.07.2022).

Venkatarama Reddy, B.V. et al. (2022), 'Codes and Standards on Earth Construction,' [in:] Fabbri, A. et al. (eds.), *Testing and Characterisation of Earth-Based Building Materials and Elements: State-of-the-Art Report of the RILEM TC 274-TCE*, vol. 35, Cham: Springer, pp. 243–259.

World Commission on Environment and Development (1987), *Our Common Future*, Oxford: United Nations, Oxford University Press.

Zare, P. et al. (2020), 'Experimental Investigation of Non-Stabilized and Cement-Stabilized Rammed Earth Reinforcement by Waste Tire Textile Fibers (WTTFs),' *Construction and Building Materials*, 260, 120432. Available at: https://doi.org/10.1016/j.conbuildmat.2020.120432 (accessed: 16.07.2022).

Zhao, X. et al. (2020), 'Evaluation of Thermal Environments for Cliff-Side Cave Dwellings in Cold Region of China', *Renewable Energy*, 158, pp. 154–166. Available at: https://doi.org/10.1016/j.renene.2020.05.128 (accessed: 16.07.2022).