

RILEM Bookseries

Christopher Beckett · Ana Bras ·
Antonin Fabbri · Emmanuel Keita ·
Céline Perlot · Arnaud Perrot *Editors*

Second RILEM International Conference on Earthen Construction

ICEC 2024



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**Second RILEM International Conference
on Earthen Construction**

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RILEM, The International Union of Laboratories and Experts in Construction Materials, Systems and Structures, founded in 1947, is a non-governmental scientific association whose goal is to contribute to progress in the construction sciences, techniques and industries, essentially by means of the communication it fosters between research and practice. RILEM's focus is on construction materials and their use in building and civil engineering structures, covering all phases of the building process from manufacture to use and recycling of materials. More information on RILEM and its previous publications can be found on www.RILEM.net.

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Preface

The RILEM International Conference on Earthen Construction (ICEC) was established in 2022 to share the knowledge emerging in the rapidly expanding research area of earthen construction materials and to welcome experts from all countries to a global knowledge-sharing network, under the sponsorship of the RILEM Association. The first event in the series was held in France at the Université Gustave Eiffel in Marne-la-Vallée, Paris, in 2022.

Earthen construction materials are some of the most familiar to humanity and yet some of the most poorly understood by engineers, architects, and designers. Over the past decades, researchers have worked to understand how these materials behave and interact with the world around them, firstly focusing on the engineering fields of strength and durability. That work created the foundation for broader investigations into how these materials regulate perceived indoor temperatures, can reduce embodied carbon, or can interact with biological agents to create strong and durable materials without relying on cementitious products.

The Second ICEC was held at The University of Edinburgh from 8 to 10 July 2024. The conference comprised plenary and parallel sessions, with keynote lectures in the areas of the realities of commercialising earthen materials, methods to preserve earthen material heritage, and advances in additive manufacturing methods to create earthen structures. These topics highlight the critical ethos behind our research: modern construction needs with a cultural responsibility.

These proceedings present the latest knowledge, understanding, and findings from multidisciplinary research groups around the world and cover topics from the behaviour of earthen materials when exposed to fire, through analyses of earthen structure performance in future climates, to how the earthen construction literature is evolving and condensing around key issues. The proceedings contain 53 technical papers, including invited papers from the conference keynote speakers and from the leaders of the three RILEM Association technical committees on earthen construction: MAE (mechanical performance and durability assessment of earthen elements and structures); BEC (bio-stabilised earth-based construction: performance-approach for better resilience); and PEM (processing of earth-based materials). All papers have been reviewed by impartial experts in the respective fields of earthen material use and behaviour.

The conference Steering Committee would like to acknowledge and thank the RILEM Association and The University of Edinburgh School of Engineering Institute for Infrastructure and Environment for their financial and administrative support for the ICEC series.

The ICEC Steering Committee:

Christopher Beckett
Ana Bras
Antonin Fabbri
Emmanuel Keita
Céline Perlot
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Contents

Additive Manufacturing and Rheology

Additive Manufacturing for Earth-Based Materials: An Experimental Investigation	3
<i>Daniel Trento, Flora Faleschini, Maryam Masoomi, Carlo Pellegrino, and Mariano Angelo Zanini</i>	
Additive Manufacturing with Earth Based Materials - Minimization of Shrinkage Deformation	12
<i>Leonie Gleiser, Robin Pierer, Slava Markin, Marko Butler, and Viktor Mechtcherine</i>	
Comprehensive Investigation into the Influence of Soil Composition and Water Content on Cracking Due to Drying Shrinkage in 3D-Printed Earthen Structures	22
<i>Betty Gonzales, Diana Zavaleta, Bruno Bertolotti, Rafael Aguilar, Miguel Pando, Javier Nakamatsu, Suyeon Kim, and Guido Silva</i>	
Developing 3D-printed Natural Fiber-Rich Earth Materials in Construction	32
<i>EunJin Shin, Olga Beatrice Carcassi, Yierfan Maierdan, Shiho Kawashima, and Lola Ben-Alon</i>	
Keeping the Processability of a Clay Mortar for Extrusion 3D Printing While Decreasing Shrinkage and Increasing the Green Strength	42
<i>Evelien Dorresteyn, Sofia Tsiotou, and Dirk Lowke</i>	
Optimisation of Earth-Based Mixtures in Terms of 3D-Printability and Mechanical Properties: Feasibility Study	52
<i>Ivan Markovic, Alexandra Horat, and Danilo Pantellini</i>	
Robotic Rammed Earth-Concrete (RREC): A Novel Additive Manufacturing Technology to Strengthen Rammed Earth Structures by Integrated Rammed Concrete Parts	60
<i>Harald Kloft, Ali Salamatian, Joshua Gosslar, Evelien Dorresteyn, and Dirk Lowke</i>	
Workflow for Earth-Based 3D-Printing	71
<i>Inka Mai, Joshua Gosslar, Noor Khader, Dirk Lowke, and Norman Hack</i>	

Monitoring and Modeling of Formwork Pressure Exerted by Castable Earth Materials	81
<i>Simon Guihéneuf, Mathieu Audren, Nathan Lely, Tangi Le Borgne, Damien Rangeard, and Arnaud Perrot</i>	
Viscosity Control of Kaolinites Dispersion via Addition of Tannin and Ferric Chloride	91
<i>Charlotte Lovage, Elodie Prud'homme, and Yves Jorand</i>	
Biostabilisation	
Challenges for Bio-Stabilised Earth-Based Construction	101
<i>Céline Perlot, Agostino Walter Bruno, Magda Posani, Guillaume Habert, and Snežana Vučetić</i>	
Mechanical and Durability Properties of GGBS- Based Geopolymer Stabilized Earth	112
<i>Diana Chami, Victor Schmitz, Pierre Gerard, and Alessia Cuccurullo</i>	
Mechanical and Thermal Characterisation of Compressed Earth Blocks Made of Termite Mound Soil (<i>Macrotermes Sp.</i>) Stabilised with Corn Starch Gel	122
<i>Berthia Malonga, Philippe Poullain, Fateh Bendahmane, Stéphanie Bonnet, Nabil Issaadi, and Louis Ahouet</i>	
Strength and Durability of Biostabilised Ghanaian Mud Bricks	132
<i>Christopher T. S. Beckett, Irene Appeaning Addo, Frederick Owusu-Nimo, Ibrahim Yakubu, Yalin Gulen, Oscar Ukwizagira, Yuner Huang, Alexandre S. Gagnon, and Ana Margarida Armada Brás</i>	
Sustainable Poured Earth Construction Using Tropical Soil and Local Wood Residue Extracts	142
<i>Lily Walter, Yannick Estevez, Gildas Medjigbodo, Adeline Armougom, Baptiste Roux, Laureline Lespinasse, Laurent Linguet, and Ouahcène Nait-Rabah</i>	
Use of Organic Residues for the Mechanical Enhancement of Sustainable Rammed Earth	152
<i>Vania Calle, Rosario Rojas, Kevin Guillen, Bartolomeo Pantò, Javier Nakamatsu, Guido Silva, and César Chácara</i>	

Characterisation and Material Behaviour

Drying-Induced Cracking of Raw-Earth Plaster	165
<i>Ghida Karbala, Patrick Belin, Julien Archez, Matthieu Vandamme, and Emmanuel Keita</i>	
Bio and Geo-Sourced Additives Influence on the Hygrothermal Properties of Earth Plaster Derived from Excavated Soil in Reunion Island	175
<i>Yannick Igor Fogue Djombou and Bruno Malet-Damour</i>	
Rammed Earth Building: Contribution of Moisture Transfer on Indoor Comfort	184
<i>Théo Poupard, Florent Fabre, Philippe Poullain, Nabil Issaadi, and Stéphanie Bonnet</i>	
RILEM Contribution to Earthen Building	194
<i>Paulina Faria, Christopher T. S. Beckett, Antonin Fabbri, Emmanuel Keita, Jean-Claude Morel, Céline Perlot, and Arnaud Perrot</i>	
Soil Stabilization with Brazilian Iron Ore Tailings to Produce Rammed Earth	206
<i>Gabriela T. L. Lage and Sofia A. L. Bessa</i>	
Workmanship Impact on Raw Earth Masonry Tensile Strength	216
<i>V. Raspail, H. Jean, P. Maillard, Y. Sieffert, Y. Malecot, F. Vieux-Champagne, and E. Crété</i>	
Assessing the Recyclability of Raw Stabilised Compressed Earth Blocks	226
<i>Mathieu Audren, Simon Guihéneuf, Tangi Le Borgne, Damien Rängeard, and Arnaud Perrot</i>	
First Findings on the Mechanical Analysis of Cob Using a Discontinuity Layout Optimization (DLO) Approach	236
<i>Alejandro Jiménez Rios</i>	
Holistic Comparison of Bio-Stabilized Rammed Earth for Building Construction	244
<i>Alessia Losini, Monika Woloszyn, Amandine Piot, Giovanni Dotelli, and Anne-Cecile Grillet</i>	
Overview of the Technical Committee MAE: Mechanical Performance and Durability Assessment of Earthen Elements and Structures	252
<i>Antonin Fabbri, Christopher Beckett, Florent Vieux-Champagne, Fionn McGregor, and Noha Al Haffar</i>	

Predicting the Hygro-Mechanical Behaviour of Stabilized Compressed Earth Bricks	261
<i>Simon-Pierre Joy Salassi, Philbert Nshimiyimana, Decroly Denouwe Djoubissie, Adamah Messan, and Luc Courard</i>	
Rammed Earth with Brick Waste and Influence of Moulding Water Content and Lime	270
<i>Ida M. G. Bertelsen, Varvara Zania, Per Goltermann, Jon Spangenberg, and Gunvor M. Kirkelund</i>	
Unsaturated Behaviour of Material from a Vernacular Eastern Croatia Rammed Earth House	281
<i>Ana Perić Fekete, Charles Augarde, Paul Hughes, and Ivan Kraus</i>	
Mechanical and Microstructural Study of Raw Earth Stabilised by Alkali-Activated Slag	291
<i>Ugo De Filippis, Elodie Prud'homme, and Sylvain Meille</i>	
Earthen Architecture and Life Cycle	
Building with Earth: How to Design Buildings Fitting Future Environmental Objectives?	303
<i>Pierre Estève-Bourrel, Christopher TS Beckett, Frédéric Bosché, Dominique Daudon, and Guillaume Habert</i>	
Sustainability of Earth-Based Materials Incorporating Marble Cutting Waste	314
<i>Giada Giuffrida, Letizia Dipasquale, Riccardo Maria Pulselli, and Rosa Caponetto</i>	
Heritage: An Inspiration for Innovation	324
<i>Ann Bourges</i>	
3D-Printed Raw Earth Structures to Create in Cities Vegetated Oasis of Coolness	332
<i>Elodie Paquet, Benoit Furet, and Arnaud Perrot</i>	
Bibliometric Analysis and Research Trends on Earthen Architecture and Construction	339
<i>Adrià Sánchez-Calvillo, Lidia Rincón, Erwan Hamard, Paulina Faria, Amanda Rivera-Vidal, Roger Vilà, Marc Medrano, and Nicolette Mafokou</i>	
Overview of Codes of Practice for Earthen Construction Around the World	348
<i>Djamalddine Boumezerane and Houcine Djeflal</i>	

Valorization of Mining By-Products for Rammed Earth Construction 356
M. A. Martin-Antunes, A. Seco, C. Perlot, and F. McGregor

Hygrothermal and Extreme Temperature Behaviour

Effect of Mechanical Loading on the Fire Behavior of compressed Earth Bricks 367
Sourour Elleuch, Rafik Abdallah, and H  l  ne Carr  

High-Temperature Performances of Compressed Earth Blocks Stabilized with Cementitious Binders 376
Philbert Nshimiymana, Kader Banaou Djibo, Seick Omar Sore, Yacouba Coulibaly, Elodie Pru'Homme, Zengfeng Zhao, Adamah Messan, and Luc Courard

Optimization of the Performance of Earth Mortars at Elevated Temperatures ... 387
Jordan Tadonbou, Prosper Pliya, Anne-Lise Beaucour, Paulina Faria, and Albert Noumowe

An Examination of Thermal Performance of Earth Construction from Theory and Practice 398
Pierre Est  ve-Bourrel, Christopher TS Beckett, Fr  d  ric Bosch  , and Julio Bros-Williamson

Capillary Absorption into 2-layer Composites Comprising of Natural Stone and Compressed Earth Blocks 409
Rafail Panagiotou and Ioannis Ioannou

Compressed Earth Blocks with Sewage Sludge Ash 419
Gunvor M. Kirkelund, Sophie S. Geyti, Thomas Lynnerup, and Ida M. G. Bertelsen

Experimental Investigation of Hygrothermal Properties of Raw Earth Compressed Blocks 428
Sara Chehade, Rahima Sidi-Boulenouar, Nicolas Dujardin, Benjamin Maillet, Jean-Didier Mertz, David Giovannacci, Emmanuel Keita, Yannick Melinge, and Abderrahim Boudenne

Impact of Rendering on Drying Stage of Light Earth Walls 438
Machhour El Assaad, Thibaut Colinart, and Thibaut Lecompte

Investigating the Thermal Conductivity of Compacted Earth Blocks Versus Density and Moisture Content 448
Nancy Hamieh, Florence Collet, Amina Meslem, Damien Rangeard, and Tangi Le Borgne

Preliminary Results of Interlaboratory Tests on Hygrothermal Properties of CEB	458
<i>Thibaut Colinart, Fionn Mcgregor, Myriam Duc, Nabil Issaadi, Lauredan Le Guen, Yacine Ferroukhi, and Abderrahim Boudenne</i>	
Investigation of Irreversible CO ₂ Interactions with Clay Minerals for the Passive Regulation of CO ₂ in Indoor Environments	466
<i>Sofia Arris-Roucan, Yi Du, Coralie Brumaud, Guillaume Habert, Céline Perlot, Fionn McGregor, Antonin Fabbri, and Guillaume Candoni</i>	
Reinforcement Behaviour	
Bonding Behaviour of Bamboo Reinforcement in Rammed Earth	475
<i>Christopher T. S. Beckett, Anca Rimniceanu, Benedicta Yi Xin Lin, and Thomas P. Reynolds</i>	
Durability Assessment of Compressed Earth Bricks (CEB) Incorporating Raw and Treated Red Algae "Gelidium Sesquipedale" Fibers	485
<i>Soukayna Talibi, Jonathan Page, Chafika Djelal, and Latifa Saâdi</i>	
Exploring the Impact of Jute Fibre Reinforcement on the Mechanical Properties of Compressed Earth Composites	495
<i>Jack Andrew Cottrell, Muhammad Ali, Alireza Tatari, D. Brett Martinson, Gary Etienne, and Colin Lupton</i>	
Mitigation of Alkali-Silica Reaction by Shredded Wind Turbine Blade Waste in Mortar	504
<i>Tao Liu, Charilaos Paraskevoulakos, and Ana T. Lima</i>	
Optimization of Mechanical Properties of Geopolymer-Stabilized Soil Using Central Composite Design	515
<i>Younes Farez, Khadim Ndiaye, Prosper Pliya, Salima Aggoun, and Romain Lafon</i>	
Author Index	525

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The following list is presenting the global offer of RILEM Publications, sorted by series. Each publication is available in printed version and/or in online version.

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Additive Manufacturing and Rheology



Additive Manufacturing for Earth-Based Materials: An Experimental Investigation

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Abstract. The achievement of sustainable development goals should be driven not only by environmental policies but also considering societal constraints, such as the valorisation of local traditions, especially in emerging countries. In the field of construction engineering, 3D printing can be seen as a modern technique which allows reproducing traditional constructions, such as those made in adobe and cob, using local and natural materials, e.g. soils, and even recycled ones, thus reducing the impacts related to the production and transport of the raw materials. The environmental and economic advantages of additive manufacturing are widely recognized for several applications: 3D printing does not require molds and allows to save material, obtaining complex shapes easily. The main advantages are linked to save money, time, handwork and properly reducing the environmental impact of structures.

In this paper the results of an experimental campaign aimed at selecting earth-based sustainable mixes for 3D printing are shown. At the beginning of the experimental campaign, 18 mixes were prepared varying the dosage and the components: among them, we selected locally available soil, silica sand, hydraulic lime binder, unaltered rice husk, shredded rice husk, marble waste dust, municipal solid waste incinerator bottom ash and fibres. Each mixture has been evaluated in terms of printability, then mechanical tests were performed at 28 days of curing. Finally, an efficiency evaluation of mixture is carried out considering compressive strength, price and embodied carbon as affecting parameters.

Keywords: 3d printing · additive manufacturing · cob · earth materials · sustainability

1 Introduction

The use of earth-based materials in the construction sector has been growing over the last few years thanks to their high recyclability and low environmental impacts [1–3]. However, their application is still limited due to high water sensitivity and lack of expertise among the stakeholders. The main issues regarding their use deal with both fresh and hardened properties, that many authors tried to address adopting the same solutions valid for concrete production [4, 5]. However, the mix-design of earth-based

materials works quite differently than concrete, thus most solutions cannot be applied achieving the same expected results.

Recently, additive manufacturing has been applied to earth-based constructions too, trying to achieve further sustainability goals by means of employing locally available [6] or waste materials [7]. Many efforts have been made indeed to automatize the construction process, seeking to reduce both construction costs and labour needed. Among the available solutions, additive manufacturing is the most studied [8, 9] because costs, impacts and time linked to formworks are almost avoided at all. Apart from this, the importance of 3D printing has grown for the ease and flexibility to create complex shapes which cannot be reproduced by other techniques.

In this context, the design of a thixotropic mixture that can be extruded easily maintaining its original shape is a typical issue in 3D printing of earth materials. Perrot et al. [10] prepared an earth-mixture containing alginate, composed of clay, kaolinite, quartz, smectite and illite, with 45% of water. Silva et al. [11] employed 5% potato scratch gel and 1% sisal fibres in combination with a well-graded soil, whereas Ferretti et al. [7] used unaltered and shredded rice husk and lime as a stabilizer to produce 3D printed earth blocks. To obtain a suitable viscosity, Gomaa et al. [12] recommended 23%-25% of water content, with 2% of straw. In this context, this work summarizes the results of a wide experimental campaign aimed to produce 3D printed earth-based constructions, which whole results are available in [13]. That work, as a result, lead to printing real-scale blocks characterized by high compressive strength (higher than 10 MPa) and very good shrinkage ($< 0.5\%$) and printability features, with reduced costs and environmental impacts.

2 Experimental Program

2.1 Materials

In this experimental campaign, the following materials were used: locally available soil, sand, rice husk, municipal solid waste incinerator bottom ash (MSWIBA), marble dust, and water. As stabilizers, a cement CEM II/B-LL 32.5 R [14] and a natural hydraulic lime NHL 5 [15] were also used for some mixes. The use of jute, coconut, sisal, and goat hair was also investigated as replacement of straw in traditional cob. This choice is justified by the fact that straw can clog the nozzle of the printer, being not suitable for additive manufacturing [16], thus alternatives were explored. Table 1 summarizes the main properties of the materials listed so far. The soil is a well-graded silty clay composed by 68.24% of clay-silt, 28.8% of sand, and 2.96% of gravels [17, 18].

2.2 Mix Design

Two sets of earth-based mixtures were prepared: the former does not contain fibres, while the latter is prepared with the natural fibres previously mentioned. Table 2 lists the mixtures prepared for this experimental campaign. The mixtures were made following the hereafter described procedure: after weighing and mixing all dried materials, the water was added and mixed with the fresh mixture; after 90 seconds, rice husk and fibres were added if required and mixed with the remaining parts.

Table 1. Physical and mechanical properties of the materials used for the 3DP mixtures.

Soil		
Atterberg limits (%)	Liquid Limit (W_L)	22
	Plastic Limit (W_P)	16
	Plastic Index (PI)	6
Density (kg/m^3)	Loose bulk density	1038.75
	Compacted bulk density	1324.75
Sand		
Density (kg/m^3)	Air-dry density	2644
	Apparent relative density	2470
	SSD density	2530
Water absorption (%)		2.71
Rice husk		
Density (kg/m^3)	Loose bulk density unaltered rice husk	95
	Loose bulk density shredded rice husk	475
Marble dust		
Density (kg/m^3)	Air-dry density	2300
	Apparent relative density	2107
	SSD density	2570
Water absorption (%)		4.5
Municipal Solid Waste Incinerator Bottom Ash (MSWIBA)		
Density (kg/m^3)	Air-dry density	2667
	Apparent relative density	2057
	SSD density	2286
Water absorption (%)		11
Cement CEM II/B-LL 32.5 R		
Compressive strength – 2 days		≥ 10 MPa
Compressive strength – 28 days		≥ 32.5 MPa
Lime NHL 5		
Compressive strength – 28 days		> 5 MPa
Fibers		
Average diameter (mm)	Jute	1.0
	Coconut	0.3
	Sisal	0.5
	Goat hair	0.2
Average length (mm)	Jute	50
	Coconut	15
	Sisal	25
	Goat hair	10
Aspect ratio (l/d)	All	50