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

Second RILEM International Conference on Earthen Construction

ICEC 2024

Springer

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RILEM Bookseries

Volume 52

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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ISSN 2211-0844 ISSN 2211-0852 (electronic)
RILEM Bookseries
ISBN 978-3-031-62689-0 ISBN 978-3-031-62690-6 (eBook)
https://doi.org/10.1007/978-3-031-62690-6

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

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
Arnaud Perrot

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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

C. Beckett et al. (Eds.): ICEC 2024, RILEM Bookseries 52, pp. 3–11, 2024.
https://doi.org/10.1007/978-3-031-62690-6_1

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