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Processing of earth-based materials: current situation and challenges ahead

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Abstract

With the overall aim of supporting the development of new construction techniques and materials that are more economical and less carbon intensive, RILEM has decided to launch three new technical committees on earth construction in 2022. One of these committees will focus on the manufacturing processes used in earth construction (TC PEM). The aim of this committee is to bring together experts from several disciplines (materials science, earth construction, rheology, geotechnics, cement chemistry, etc.) to advance earth construction techniques by sharing and promoting good practice. The processing of earth is today based on solid empirical knowledge which fails to convince structural design engineers. As a result, earth construction is still limited to small buildings. To upscale the use of earthen material in construction, it is required to provide a solid scientific background that can be used for the writing of standards and recommendations to guarantee minimal performances in service. Areas of work include improving understanding of the mechanical behaviour of the material in the fresh state, developing characterization methods, monitoring the material during curing, and studying new construction techniques, particularly digital ones. The work of the technical committee PEM "Processing of earth-based materials" is expected to gather the scientific knowledge that can be further used for the writing of construction and design codes for earthen materials.

Keywords: Earthen materials; Rheology; Processing; Drying; Shrinkage; Additive manufacturing

1 Introduction

The construction sector must contribute to limit global warming by drastically limiting natural resource depletion and rapidly tending to a net zero carbon balance. In this regard, construction methods and materials should evolve using local materials with low or limited embodied carbon. Consequently, earth is a great opportunity as a construction material to supplement concrete or fired clay in many applications.

Earth is one of humankind's oldest building materials and is still present worldwide [1,2]. Currently, the interest in earth-based building materials is revived by their low environmental impact and the need to answer global warming issues. Indeed, the building sector contributes by a significant share to entropic carbon emissions [3,4]. Moreover, earth is a resource available worldwide that fits a circular economy and local economic development [5]. In this context, earth appears as a promising solution for carbon reduction, recycling, and reuse in the construction sector [6,7].

Earth has to be processed to become a construction material. It is excavated from soils, prepared at a specific water content which can be varied to reach a specific consistency. At this water content and for processing purposes, earth is at its fresh state. At early age, after being processed, raw earth starts to harden due to the water removal due to the drying process (note that hardening can occur due to chemical reactions when studying stabilised earth). When the drying process ends, earth reaches its hardened state with almost stable mechanical properties and can be used as a construction material.

It is worth noting that earthen materials can be processed at different consistencies using a large variety of methods. In a liquid state with a high water content, fresh state earth can be self-flowable and cast in formwork. In a plastic state, the material is shapable and can be extruded to make construction blocks or can be manually shaped into balls to build cob walls. In a dryer state or with a higher sand or aggregate content, earth can be rammed into blocks or walls. This variety of processes makes earthen constructions difficult to be unified in a single fashion.

However, earth-based material faces many challenges to be considered relevant modern building material. The variability of the resources should be integrated with the formulation strategy [8]. At the hardened state, water sensitivity should be better assessed [9–11]. At fresh state, vernacular techniques such as cob, rammed earth, wattle and daub or adobes masonry and new processes such as self-flowable

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earth or digitally-aided methods need a scientific review in order to obtain better control of material quality and prediction of the hardened properties [12,13]. The work of the technical committee (TC PEM “Processing of earth-based materials”) does not target specific processing routes but aims to provide a global overview of all possible construction techniques, from traditional methods to digital ones, with related fresh-state requirements. The goals are to explain the fresh-state behaviour of earth and its range of possible consistencies based on a microstructural description, to collect and/or define suitable test methods to measure physical parameters linked to the rheological behaviour, and to study the behaviour of the earth just after being processed during the drying stage. Finally, new and vernacular processes can be described based on fresh-state requirements and properties of the earth microstructure (particle size distribution, clay mineralogy).

The technical novelty applied to earth-based materials generates complex inter-disciplinary problems; moreover, processing requirements usually play a key role in the mix design. Robotics and Information Technologies allow revisiting most building processes. For the last decade, new construction processes have been developed with digital tools. These innovations were also related to better formulation control of cement-based materials [14–17]. Similar contributions now focus on earth-based materials [18–20].

New techniques and formulations are real opportunities for earth. As vernacular techniques are not well standardized, they could be directly included in the general effort on earth material characterization and discussions on standards. Indeed, the evolution should align with the broader goal of maintaining the environmental benefit of earth materials.

Like for any other construction materials, it is required to carry out tests on earth-based materials to check the earthen material suitability to be processed with a specific method (like the Abrams cone test is used for concrete casting), to verify the material homogeneity during the construction process and to be used as a quality control test. In recent years, various rheometric and characterization tests have been developed for earth-based building materials. However, some large scope aspects often need to be improved and should be discussed by the scientific community. Indeed, the underlying behaviour is postulated but only partially assessed. For instance, materials are often considered purely plastic. However, they may also exhibit frictional and viscous behaviour. These contributions should be considered in the description of processing routes. Moreover, depending on the mineralogical nature of fine particles, particle size distribution, and water content, earth can show an extensive range of behaviour from very fluid to granular-like. The boundary between these different types of behaviour should be linked to the material microstructure, and shared rheological tools should be adopted for each earth consistency.

Although mix design mainly impacts rheology, its influence on drying and mechanical build-up is detrimental. It is necessary to avoid cracks, limit shrinkage, and obtain homogenous materials. Indeed, new formulations with additives offer ways to reduce the water content and suppress cracks while improving mechanical behaviour. There is a need to understand the underlying physics behind the additives effect to have mix-design strategies not only based on trials and errors and empirical methods.

This paper will present the objectives and organization of the technical committee “Processing of earth-based materials” (PEM) and locate its position within the RILEM network by identifying the link with the other active TCs. Additionally, the key research interests called work packages that build the structure of the TC PEM will also be presented. The research needs and objectives of the TC will be provided.

2 Aim and organization of the Technical Committee

The primary objective of the Technical Committee (TC) “Processing of Earth-based Materials” is to thoroughly investigate the characteristics and conduct of earth-based materials during their initial state and the subsequent hardening process. Specifically, the TC will concentrate on addressing issues related to the fresh state and early age (related to the drying stage) properties of earthen materials (i.e. all kinds of excavated soils or clay and silt-rich mineral by-products and waste such as quarry wash muds or sediments).

Furthermore, the scope of this TC extends to encompass emerging techniques currently under development. This includes novel methodologies like extrusion-based 3D printing and poured earth construction, which are thoroughly examined and explored within the context of earth-based materials processing.

The kick-off meeting was held on June 9th 2022 and the TC is expected to last five years, during which extensive research and analysis is conducted. The aim is to bring together experts and researchers from academia and private sectors within the scientific community. Notably, the 106 members of TC PEM (RILEM website inscription on October 12th 2023) are primarily located in Europe, North America, and Asia. However, proactive efforts are currently made to include members from industry (13 members) and from Africa (3 members) where earth construction can be considered a great opportunity for the development of sustainable construction [21]. The targeted users of the TC outcomes are researchers, engineers, and practitioners.

The expected primary achievement of this TC is to provide an extensive literature review on advancements made in the field of fresh state and early age characteristics of earth-based materials since the 2000s. A RILEM State-of-The-Art-Report is expected at the end of 2024. This comprehensive review will serve as the foundation for subsequent phases of research, which may involve round-robin testing in a second phase, between 2025 and 2027, or in a subsequent TC.

Indeed, mix-design strategies are complex, and the relevant parameters must be clearly identified. At this stage, it seems appropriate to federate a growing community, harmonize test methods, and define terminology.

Four main investigation topics have been identified and provide the structure of the TC:

1) to describe the rheological behaviour of earth materials.
2) to define the rheometric characterization tools suitable for earth materials
3) to describe curing and early-age behaviour.
4) to describe new processes

These four topics define the Work Packages (WP) structuring the Technical Committee. It is important to keep in mind that the four topics are highly connected (Figure 1) and that the working groups acting in the framework of the corresponding work packages have to work together and develop links. For example, the working group on new processes (WP4) requires a precise description of the rheological models that can be suitable for earthen materials (WP1), how to measure them (WP2) and anticipate the effect of curing and drying (WP3) on the processed materials to lead the process to success.

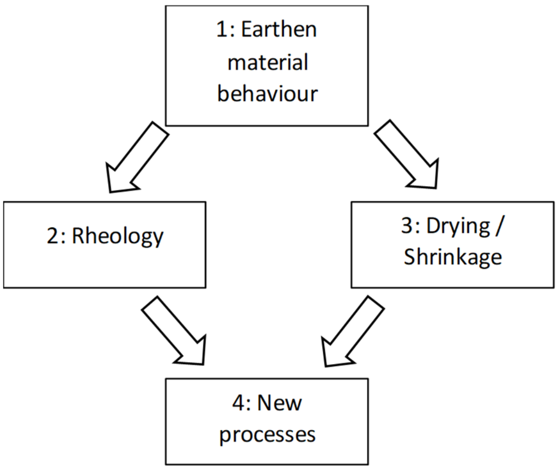

Figure 1: TC Organization

These four work packages will be presented in the following sections.

3 Rheology of earth-based systems

The precise description of the microstructure and physico-chemical properties of the cementitious materials at the fresh state has allowed making disruptive jump in the concrete industry, including the design of self-compacting mixes [22], of ultra-high-performance concrete [23] and now on the development of 3D concrete printing [15,16]. Understanding the interactions at stake at the microscale has made it possible to design very efficient additives like superplasticizers, and viscosity modifying agents [24–26], to improve the mix-design methods [26], and to develop prediction equations for the macroscopic rheological behaviour [28]. This link between the microstructural properties and the flow behaviour of cement-based materials can be called rheophysics and uses the underlying physics of interaction at the microscale to explain the fresh-state properties of cementitious materials.

This developed knowledge is currently lacking for earthen materials and there is a considerable temptation to mimic the concrete industry to reach the same level of expertise. Only a few studies currently try to relate the fresh-state microstructure of earthen construction to the fresh-state behaviour regarding the huge variability of earthen materials, possible admixtures and processing methods [8,29,30].

A basic rheological behaviour such as the Bingham model, commonly used to model the concrete flow [31], with two modelling parameters (yield stress, viscosity) cannot represent well enough shear and compression behaviour of every type of earthen material which is a complex heterogeneous material (interstitial fluid, entrapped air and particles with a broad size distribution). The microstructure and interactions at stake, the role of clay, in relation to its mineralogical nature, need to be described as well as the effect of admixtures, in particular bio-sourced ones.

It is also worth noting that earthen materials may present a huge variability of consistencies from liquid to granular-like according to the initial water content w% (Figure 2). The term consistency refers to geotechnical or concrete workability classes that need to be translated in terms of rheological behaviour to provide a common terminology to the earthen construction community. Moreover, it is necessary to find the boundaries for these consistency types that can provide fresh-state behaviour classification in relation to mix-design parameters like done for cementitious materials [32].

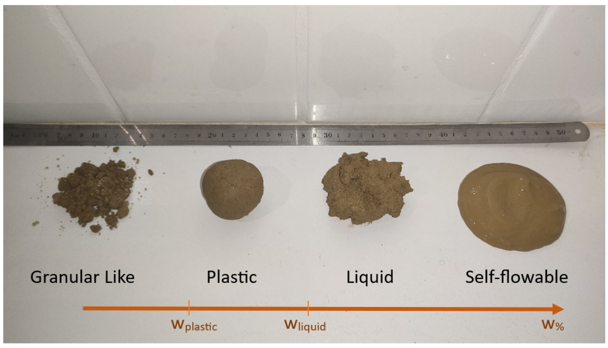

Figure 2: Possible earth consistencies of a same earthen material with increasing water content in relation with the Atterberg consistency limits commonly used in geotechnics.

Therefore, a working group of the technical committee targets to provide a theoretical frame for these requirements:

- Define earth-based material behaviours and categories of classification based on the composition (clay content, particle size distribution, volume fraction…).
- Provide a common terminology to make geotechnicians, rheologists, earthen and cementitious materials scientists working together efficiently.
- Find suitable rheological or mechanical models for each type of earthen material consistency.
- Assess the suitability of the earthen resources to a specific technique.
- Describe the working mechanisms of admixtures.

Before developing new knowledge through collaboration, the collection of existing literature to write a state-of-the-art report about the rheo-physics of cementitious materials, which starts from the description of earthen materials microstructure including particle size distribution, mineralogy and morphology, types of interaction at stake: Van der Waals, Electrostatic, friction, saturation degree (suspensions/ granular-like materials), solid packing fractions....

This state-of-the-art will also present all mechanical models that are used to describe the fresh-state behaviour of earthen materials, including rheological models and geotechnical or poro-mechanics models that can be helpful for unsaturated or granular-like materials [33]. It also aims to link the observed behaviour to suitable construction methods by trying to collect the fresh-state requirements for each processing method (casting, shaping, Ramming, etc.). The last part of this state-of-the-art methods will address the effects of admixtures on the rheological and fresh state behaviour, such as dispersants, coagulants, and viscosity modifiers. Their impact on the initial behaviour of the earth but also on a possible time-evolution of the mechanical behaviour due to hardening or gelling will be gathered, especially in order to help for the optimization of new processes such as pourable earth and earth 3D printing.

4 Rheological characterization of earth materials

Many rheological characterization tools and methodologies have been developed in many laboratories to deal with the description of the behaviour of fluid to stiff pastes or even granular-like materials [33]. These methods are adapted from different scientific disciplines, such as rheology, geotechnics, or concrete sciences; and there is a huge need to share these practices and promote the most convenient and precise ones. As a result, penetration tests, rheological methods, gravity-induced deformation tests or mechanical testing methods have already been used to describe the fresh-state properties of earthen materials (Figure 3) [34–36].

In addition, contrarily to cementitious materials or soils, no common practices or standards can be used as a reference for earthen materials. The diversity of earthen materials consistency and earthen materials processing methods can explain this lack of common practices.

Moreover, most of the techniques used on-site to characterize the fresh state behaviour of earthen materials are empirical. They are not currently used to compute intrinsic mechanical or rheological behaviour parameters.

Consequently, there is a considerable need to evaluate these existing methods to provide the physical basis that can allow us to compute behaviour parameters and finally harmonize practices.

In the framework of the technical committee, a working group has started to review existing methods and evaluate their ability to be used as quality control methods (accuracy, representative volume of materials, implementation easiness, etc.) or assess the possibility of computing behaviour parameters from the test results. Once this review work is done (after 2024), an inter-laboratory study will be organized to verify the relevance of the methods and define common procedures (first step toward recommendations).

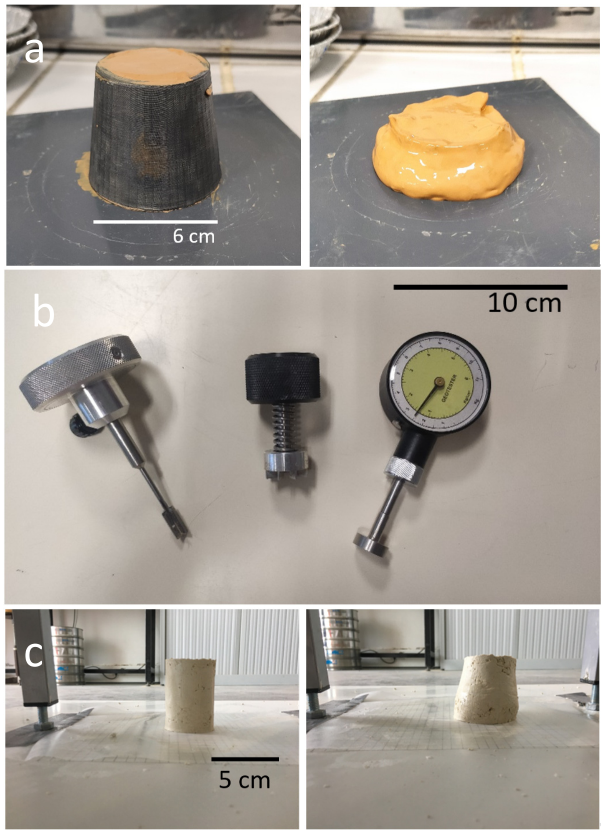

Figure 3: Characterization methods used for earthen construction: a) slump flow (inspired by concrete technology) - b) Pocket handy cone penetration and vane test devices (inspired by geotechnical engineering) - c) dropping cylinder test: sample before and after being dropped (inspired by empirical methods used in vernacular construction).

The work carried out on the topic is then expected to present efficient solutions to estimate parameters of the fresh state behaviour of earthen materials that are relevant to predict the material processing. These parameters include characteristics linked to so-called earth consistency (Yield stress, viscosity, internal and surface friction, critical strain) but also to other parameters that can be relevant in earthen materials digital construction, such as structural build-up rate or elastic modulus [18].

Table 1: Summary of available test methods for earthen materials with expected advantages and drawbacks.

Tests		Test location		Earth consistency			Advantages	Drawbacks
		In-situ	Laboratory	Liquid	Plastic	Granular		
Rotational rheometry (i.e. vane test, concentric cylinders)	Portable	x	x	x	x	x	Simple, cheap	Lack of accuracy
	Manual lab		x	x	x	x	Accurate	Limited to lab
	Rheometer		x	x	x		Very accurate	Limited to lab
Penetrometer (cylinder, hemisphere, cone, …)	Portable	x	x	x	x	x	Simple, cheap	Lack of accuracy
	Manual lab		x	x	x	x	Accurate	Limited to lab
	Loading machine		x	x	x		Very accurate	Limited to lab
Gravity induced test	Slump flow	x	x	x			Simple, cheap	Narrow range of consistency
	Spread flow	x	x	x			Simple, cheap	Narrow range of consistency
Dropping object	Spheres	x	x		x	x	Simple, cheap	Only qualitative results
	Cylinders	x	x		x	x	Simple, cheap	Difficult to perform - vertical fall
Capillary flow and extrusion	Loading machine		x		x		Accurate	Narrow range of consistency - requires a loading machine
Shear box test	Loading machine		x		x	x	Accurate	Requires a loading machine
Compression test	Loading machine		x		x	x	Accurate	Requires a loading machine

Moreover, it is worth noting that the efficient methods that allow for the accurate determination of one modelling parameter of the fresh-state behaviour can also depend on the flow regime and the consistency of the earthen materials [36]. As a result, the work to describe the rheophysics of earthen materials will be helpful in defining consistency classes that can suit processing methods and fresh-state characterization tools. For earth, tools used in geotechnics are expected to be relevant for granular-like materials (for example, cone penetration, shear box or triaxial test). At the same time, empirical methods like the slump test or rheological methods, for example rotational rheometry such as vane test methods, are likely to be efficient in studying the fresh-state behaviour of flowable earth. A summary of available test methods is provided in Table 1 with their expected advantages and drawbacks. In this table, the possibility of using the test on-site and the suitability of the test for a given range of consistency is provided

5 Curing and early-age behaviour

The primary objective of this research is to investigate the drying stage in the processing of earth-based materials, which plays a crucial role in determining the pace of construction. During this stage, the microstructure consolidation and mechanical properties gradually develop. However, addressing challenges such as shrinkage, cracks (Figure 4), and heterogeneities is essential, as they can adversely affect the final structure. Additionally, the role of fibers and stabilisers in the drying process is currently being examined.

This study aims to achieve the following outcomes:

A comprehensive review of drying phenomena in earth-based materials: The research is expected to provide an in-depth understanding of the various aspects related to the drying stage, including the underlying mechanisms, influencing factors, and potential challenges.

A review of tests to assess drying and mechanical build-up kinetics will be performed. For all topics, the existing literature is being collected, and a particular focus is paid to the experimental protocol. The description of the drying process and its effect on the mechanical and dimensional stability of earthen materials is expected to provide a theoretical framework that can be used efficiently to optimize the curing conditions and find mix-design solutions that can mitigate the possible detrimental effects of drying.

It is important to note that many techniques exist to describe the drying process and evaluate its effect in terms of dimensional stability (shrinkage), strength and structural integrity (cracks). These methods are different and can be based on monitoring the water content and distribution within the earthen material, direct or indirect measurements of the dimensions of samples (using rulers, gauges or optical methods such as DIC or 3D scan), and defect detection methods that can be used to detect cracks formation.

Given the potential scarcity of literature dedicated specifically to methods and standards for earthen materials, this review encompasses materials closely related to earthen building materials, including concrete, fired earth, and soils [37–39]. The suitability of these materials for monitoring the early-age evolution of earthen materials is also evaluated as potential candidates. This comprehensive approach will enhance our understanding of drying processes and their effects on various materials, facilitating advancements in the field of earthen construction and preservation.

Indeed, the question of the range of expected and suitable shrinkage for earthen construction materials should be discussed in comparison to cementitious materials, for instance. It can be interesting to provide specifications on the shrinkage limits depending on the process. As a result, special care is taken to identify the specificity of earthen materials as the physics may be too different between low and high-porous materials, and there can be a problem with the amplitude difference between the low shrinkage of concrete in comparison with the one that can occur with clayey materials.

The work must intend to propose an experimental test to measure the shrinkage. However, it is first important to precisely understand the mechanisms. By achieving these objectives and obtaining the expected results, this research will contribute to advancing knowledge and providing practical insights for optimizing the drying process of earth-based materials in construction applications.

After the state-of-the-art report, an interlaboratory study could be organized. This study will compare and refine experimental methods and protocols to effectively evaluate the kinetics of both drying and the development of mechanical properties during the drying stage. These tests will serve as valuable tools for assessing the performance and behaviour of earth-based materials under different drying conditions.

The WP should also address the main way studied to promote dimensional stability and increase early age tensile strength with the combined objectives of reducing shrinkage and preventing cracking. The impact of additives like fibres, biopolymers, or other solutions like sand inert particles or stabilisers is extensively studied to improve these early-age performances, considering potential environmental drawbacks. It is worth noting that the study of the use of biopolymers for enhancing crack resistance and limiting shrinkage is performed in relation to Technical Committee BEC "Bio-stabilised earth-based construction: performance-approach for better resilience".

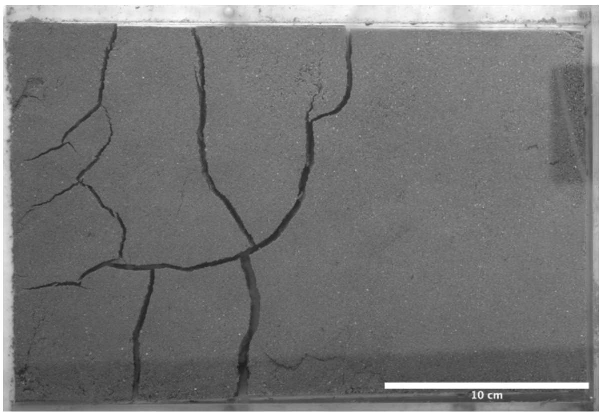

Figure 4: Dried montmorillonite mortar on a Teflon plate with varying thickness: thickness increases from left to right. The varying thickness induced a heterogeneous volume change during drying leading to cracks formation (Internship G. Karbala, 2023)

6 New processing methods

Progresses in material sciences and automation in construction allow us to envisage new processing methods for earthen materials [19]. Hence, digital fabrication is a new technique for building materials combining trends of robotics while targeting sustainability. Moreover, the implementation of self-flowable earth is also an attractive prospect as earth would be cast with conventional concrete processes. These new processing routes are now focusing attention and can be considered promising opportunities for the future of earthen construction.

Considering poured self-flowable earth, pioneering works were carried out in the early 2010s at ETH Zurich and Lyon [29,40–42] based on the application of concrete mix-design solutions and on the development of hardening solutions that allow the removal of the formwork in a reasonable amount of time. Since then, many studies have tried to develop new solutions for adapting earthen materials using admixtures or stabilisers, often bio-based, and there is a real need to gather all works in a review work that can help to compare and evaluate the actual processes. The use of admixtures and stabilisers also changes the hardened properties by increasing the strength and improving the water resistance [43–46]. Still, it impacts the carbon footprint of the earthen materials designed for casting operations. In this case, the benefits and drawbacks of the use of admixtures must be balanced or at least listed.

It is also worth noting that due to the increased scarcity of natural resources, the rise in the price of energy has made fired earth brick manufacturers question themselves about the opportunity to adapt their industrial tools and reuse their production line equipments (mainly industrial extruders) to stabilise earth construction blocks. This question could then also be addressed in the framework of this topic on new processing methods.

Simultaneously, many studies deal with adapting earthen materials to digital fabrication using many different methods, such as extrusion [18,47], ball placing [48], sprayed earth, or automated rammed earth [19,20] (Figure 5). It is worth noting that this diversity in digital fabrication methods is like the one found in vernacular construction methods. Therefore, it is attempting to try to unify the different technologies between vernacular construction and newly developed digital processes that have appeared in recent years. An interesting classification of the vernacular earthen construction method is the one proposed by Auroville Earth Institute [49]. An appealing idea is to promote the opportunity to revive traditional techniques using digital manufacturing technologies.

As a first working program, three objectives have been defined to build a state-of-the-art of the new processing methods:

- Documentation of traditional construction techniques for earth-based materials and elaborate on material preparation and handicraft processing techniques.
- Review of current digital and industrial processes with earth-based materials that take up traditional construction methods and elaboration of material specifications and process characteristics.

- Review of novel digital fabrication strategies with earth-based materials and elaboration of material specifications and process characteristics.

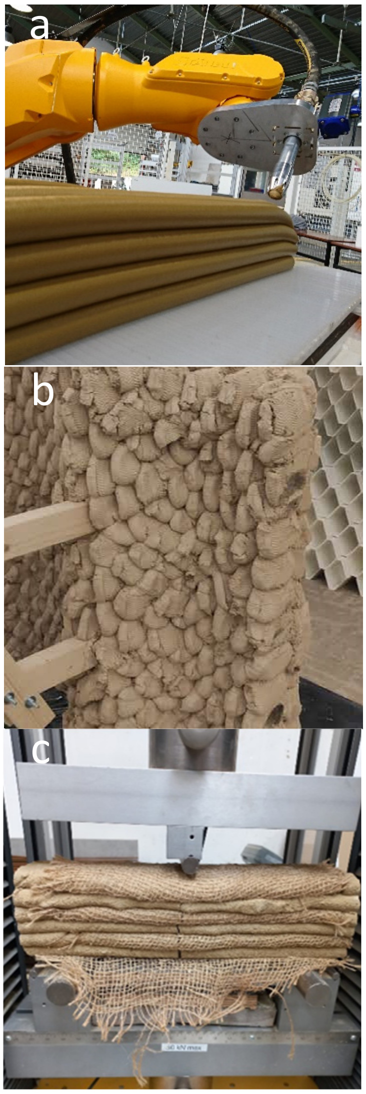

Figure 5: Digitally fabricated earthen materials: a) Extrusion process of clay by the 3D printer (same set up as in [18])- b) Digitally fabricated cob-like structures (ETH Zurich) - c) 3D printed earth samples with bio-based net reinforcement.

Moreover, the material and process interactions should be described. This study will likely lead to the definition of process characteristics and material specifications.

Some of the digital processing methods require the use of a setting-like agent to ensure that the built structure remains stable during processing. In this case, the effect of the setting-like agent is not limited to the processing step but will also influence the hardened properties and the carbon footprint. It is also expected to collect data to estimate the life cycle assessment of structures built digitally with a setting-like agent to verify if these developed solutions remain environmentally pertinent and keep the advantages of sustainability of earthen construction.

It is also interesting to note that some of the products used for the 3D printing of earthen materials are bio-based and have been used for centuries in vernacular earthen construction methods. Such a statement strengthens our objective to get vernacular and new earthen construction methods closer.

7 Position of the TC in the RILEM network

This Technical Committee was established in collaboration with two other TCs focused on earthen construction, namely "MAE: Characterisation of the mechanical performance and durability of earthen materials and structures" and "BEC: Bio-stabilised earth-based construction: performance-approach for better resilience” in order to foster a community dedicated to advancing knowledge in this field.

Moreover, these three TCs serve as a continuation of the TC 274-TCE "Testing and characterisation of earth-based building materials and elements," which was active from 2016 to 2022. The collaboration between these TCs allows for the seamless progression of research and knowledge sharing within the domain of earth-based construction materials. It can be reminded that the first RILEM recommendation on earth construction dates from 1996 with the work of the committee TC 164-EBM Mechanics of earth as a building material [50] and that no RILEM action related to earth construction occurred between 1996 and 2016.

To maximize the impact of activities undertaken at RILEM on earth construction, concerted efforts have been made to establish common dissemination and communication channels between the three Technical Committees (BEC, MAE and PEM). These collaborative endeavours aim to enhance the visibility and reach of the research and initiatives carried out by the TCs focused on earthen construction. By fostering close coordination and collaboration in disseminating findings, the collective impact and influence of the TCs' endeavours are significantly amplified. Through the implementation of shared communication strategies, including joint publications, conferences, workshops, and outreach activities, the dissemination efforts of the TCs are effectively aligned to create a coherent and impactful message within the broader RILEM community and beyond.

In close collaboration with the two other TCs on earthen construction, the international conference on earthen construction will be organized every two years during the lifetime of this TC, following the model of the first conference organized by E. Keita and held in Paris at University Gustave Eiffel in March 2022. Following the same frequency, and possibly in connection with these conferences, doctoral schools on some scientific topics related to earthen construction will also be proposed.

Additionally, this TC maintains connections with other TCs that focus on rheology and 3D printing techniques. These include TC 266-MRP: "Measuring Rheological Properties of Cement-based Materials," TC PFC: "Performance requirements and testing of fresh printable cement-based materials," and TC ADC: "Assessment of Additively Manufactured Concrete Materials and Structures." The interlinking of these TCs facilitates interdisciplinary collaborations and the exchange of expertise in the areas of material rheology and advanced printing methodologies.

8 Conclusions

Earth-based materials are positioned to play a vital role in sustainable construction, addressing global warming and resource conservation. The Technical Committee "Processing of Earthen Materials" (PEM) leads efforts to advance knowledge in this field, collaborating with related RILEM TCs. PEM's focus encompasses fresh state and early age properties, with particular attention to rheological behaviour, characterization tools, curing, and innovative processing methods. It underscores the importance of establishing consistency classes and standardized terminology for effective collaboration across disciplines.

Moreover, the study explores the challenges of drying and early-age behaviour, particularly regarding shrinkage and cracks, while scrutinizing the environmental impact of additives used in emerging processing techniques. The comprehensive approach outlined in this work promises to shape the future of sustainable construction materials and methods, facilitating a transition towards more eco-friendly and efficient building practices.

In this context, the TC's recommendations will be diffused to national and multi-national groups to promote these practices. This dissemination is crucial for promoting sustainable construction practices and a more eco-friendly and efficient future in building construction.

Authorship statement

Arnaud Perrot : Conceptualization, Writing - original draft, Writing - review and editing

Emmanuel Keita : Conceptualization, Writing - original draft, Writing - review and editing

References

[1] V. Maniatidis, P. Walker, A review of rammed earth construction, Innovation Project "Developing Rammed Earth for UK Housing", Natural Building Technology Group, Department of Architecture & Civil Engineering, University of Bath. 12 (2003).

[2] F. Pacheco-Torgal, S. Jalali, Earth construction: Lessons from the past for future eco-efficient construction, Construction and Building Materials. 29 (2012) 512-519. https://doi.org/10.1016/j.conbuildmat.2011.10.054

[3] G. Habert, C. Billard, P. Rossi, C. Chen, N. Roussel, Cement production technology improvement compared to factor 4 objectives, Cement and Concrete Research. 40 (2010) 820-826. https://doi.org/10.1016/j.cemconres.2009.09.031

[4] G. Habert, S.A. Miller, V.M. John, J.L. Provis, A. Favier, A. Horvath, K.L. Scrivener, Environmental impacts and decarbonization strategies in the cement and concrete industries, Nature Reviews Earth & Environment. 1 (2020) 559-573. https://doi.org/10.1038/s43017-020-0093-3

[5] Ö. Çimen, Construction and built environment in circular economy: A comprehensive literature review, Journal of Cleaner Production. 305 (2021) 127180. https://doi.org/10.1016/j.jclepro.2021.127180

[6] E. Hamard, B. Cazacliu, A. Razakamanantsoa, J.-C. Morel, Cob, a vernacular earth construction process in the context of modern sustainable building, Building and Environment. 106 (2016) 103-119. https://doi.org/10.1016/j.buildenv.2016.06.009

[7] L. Verron, E. Hamard, B. Cazacliu, A. Razakamanantsoa, M. Duc, T. Vinceslas, A.H. de Menibus, B. Lemercier, R.J. Ansaa-Asare, T. Lecompte, Estimating and mapping the availability of earth resource for light earth building using a soil geodatabase in Brittany (France), Resources, Conservation and Recycling. 184 (2022) 106409. https://doi.org/10.1016/j.resconrec.2022.106409

[8] D. Ardant, C. Brumaud, A. Perrot, G. Habert, Robust clay binder for earth-based concrete, Cement and Concrete Research. 172 (2023) 107207. https://doi.org/10.1016/j.cemconres.2023.107207

[9] S. Guihéneuf, D. Rangeard, A. Perrot, T. Cusin, F. Collet, S. Prétot, Effect of bio-stabilizers on capillary absorption and water vapour transfer into raw earth, Materials and Structures. 53 (2020) 138. https://doi.org/10.1617/s11527-020-01571-z

[10] P. Chauhan, A. El Hajjar, N. Prime, O. Plé, Unsaturated behavior of rammed earth: Experimentation towards numerical modelling, Construction and Building Materials. 227 (2019) 116646. https://doi.org/10.1016/j.conbuildmat.2019.08.027

[11] T. Chitimbo, N. Prime, O. Plé, F. Abdulsamad, Drying experiment on rammed earth structure, European Journal of Environmental and Civil Engineering. 27 (2023) 2950-2966. https://doi.org/10.1080/19648189.2022.2099983

[12] A.W. Bruno, D. Gallipoli, C. Perlot, J. Mendes, Mechanical behaviour of hypercompacted earth for building construction, Materials and Structures. 50 (2017) 1-15. https://doi.org/10.1617/s11527-017-1027-5

[13] A. Perrot, D. Rangeard, F. Menasria, S. Guihéneuf, Strategies for optimizing the mechanical strengths of raw earth-based mortars, Construction and Building Materials. 167 (2018) 496-504. https://doi.org/10.1016/j.conbuildmat.2018.02.055

[14] A. Perrot, D. Rangeard, A. Pierre, Structural built-up of cement-based materials used for 3D-printing extrusion techniques, Materials and Structures. 49 (2016) 1213-1220. https://doi.org/10.1617/s11527-015-0571-0

[15] N. Roussel, Rheological requirements for printable concretes, Cement and Concrete Research. 112 (2018) 76-85. https://doi.org/10.1016/j.cemconres.2018.04.005

[16] T. Wangler, E. Lloret, L. Reiter, N. Hack, F. Gramazio, M. Kohler, M. Bernhard, B. Dillenburger, J. Buchli, N. Roussel, Digital concrete: opportunities and challenges, RILEM Technical Letters. 1 (2016) 67-75. https://doi.org/10.21809/rilemtechlett.2016.16

[17] T. Wangler, R. Pileggi, S. Gürel, R.J. Flatt, A chemical process engineering look at digital concrete processes: critical step design, inline mixing, and scaleup, Cement and Concrete Research. 155 (2022) 106782. https://doi.org/10.1016/j.cemconres.2022.106782

[18] A. Perrot, D. Rangeard, E. Courteille, 3D printing of earth-based materials: Processing aspects, Construction and Building Materials. 172 (2018) 670-676. https://doi.org/10.1016/j.conbuildmat.2018.04.017

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

[20] M. Gomaa, W. Jabi, V. Soebarto, Y.M. Xie, Digital manufacturing for earth construction: A critical review, Journal of Cleaner Production. 338 (2022) 130630. https://doi.org/10.1016/j.jclepro.2022.130630

[21] M. Sonebi, A. Abdalqader, S. Amziane, L. Dvorkin, E. Ghorbel, S. Kenai, J. Khatib, N. Lushnikova, A. Perrot, Trends and opportunities of using local sustainable building materials in the Middle East and North Africa region, RILEM Tech Lett. 7 (2022) 127-138. https://doi.org/10.21809/rilemtechlett.2022.169

[22] K. Kovler, N. Roussel, Properties of fresh and hardened concrete, Cem Concr Res. 41 (2011). https://doi.org/10.1016/j.cemconres.2011.03.009

[23] H. Bahmani, D. Mostofinejad, Microstructure of ultra-high-performance concrete (UHPC)-A review study, Journal of Building Engineering. 50 (2022) 104118. https://doi.org/10.1016/j.jobe.2022.104118

[24] R.J. Flatt, Polymeric dispersants in concrete, Polymers in Particulate Systems: Properties and Applications. (2001) 247-294. https://doi.org/10.1201/9781482271119-15

[25] R. Flatt, I. Schober, Superplasticizers and the rheology of concrete, in: Understanding the Rheology of Concrete, Elsevier, 2012: pp. 144-208. https://doi.org/10.1533/9780857095282.2.144

[26] P.-C. Aïtcin, R.J. Flatt, Science and technology of concrete admixtures, Woodhead publishing, 2015. ISBN: 9780081006931

[27] O. Ahmadah, H. Bessaies-Bey, A. Yahia, N. Roussel, A new mix design method for low-environmental-impact blended cementitious materials: Optimization of the physical characteristics of powders for better rheological and mechanical properties, Cement and Concrete Composites. 128 (2022) 104437. https://doi.org/10.1016/j.cemconcomp.2022.104437

[28] R.J. Flatt, P. Bowen, Yodel: a yield stress model for suspensions, Journal of the American Ceramic Society. 89 (2006) 1244-1256. https://doi.org/10.1111/j.1551-2916.2005.00888.x

[29] Y. Du, G. Habert, C. Brumaud, Design of Tannin-Based Poured Earth Material via Deflocculation-Coagulation Control: Additive Selection and Tannin Variation, ACS Sustainable Chemistry & Engineering. 10 (2022) 14495-14502. https://doi.org/10.1021/acssuschemeng.2c04078

[30] G. Landrou, C. Brumaud, M.L. Plötze, F. Winnefeld, G. Habert, A fresh look at dense clay paste: Deflocculation and thixotropy mechanisms, Colloids and Surfaces A: Physicochemical and Engineering Aspects. 539 (2018) 252-260. https://doi.org/10.1016/j.colsurfa.2017.12.029

[31] G.H. Tattersall, P.F.G. Banfill, The rheology of fresh concrete, Pitman Advanced Publishing Program, London, 1983.

[32] [32] N. Roussel, A. Lemaître, R.J. Flatt, P. Coussot, Steady state flow of cement suspensions: A micromechanical state of the art, Cement and Concrete Research. 40 (2010) 77-84. https://doi.org/10.1016/j.cemconres.2009.08.026

[33] D. Gallipoli, A.W. Bruno, C. Perlot, J. Mendes, A geotechnical perspective of raw earth building, Acta Geotechnica. 12 (2017) 463-478. https://doi.org/10.1007/s11440-016-0521-1

[34] A. Perrot, D. Rangeard, T. Lecompte, Field-oriented tests to evaluate the workability of cob and adobe, Materials and Structures. 51 (2018) 1-10. https://doi.org/10.1617/s11527-018-1181-4

[35] J. Tourtelot, I. Ghattassi, R. Le Roy, A. Bourgès, E. Keita, Yield stress measurement for earth-based building materials: the weighted plunger test, Materials and Structures. 54 (2021) 1-13. https://doi.org/10.1617/s11527-020-01599-1

[36] A. Perrot, D. Rangeard, A. Levigneur, Linking rheological and geotechnical properties of kaolinite materials for earthen construction, Materials and Structures. 49 (2016) 4647-4655. https://doi.org/10.1617/s11527-016-0813-9

[37] P. Lura, O.M. Jensen, K. Van Breugel, Autogenous shrinkage in high-performance cement paste: An evaluation of basic mechanisms, Cement and Concrete Research. 33 (2003) 223-232. https://doi.org/10.1016/S0008-8846(02)00890-6.

[38] M. Wyrzykowski, S.-I. Igarashi, P. Lura, V. Mechtcherine, Recommendation of RILEM TC 260-RSC: using superabsorbent polymers (SAP) to mitigate autogenous shrinkage, Mater Struct. 51 (2018) 135. https://doi.org/10.1617/s11527-018-1241-9.

[39] S. Markin, V. Mechtcherine, Quantification of plastic shrinkage and plastic shrinkage cracking of the 3D printable concretes using 2D digital image correlation, Cement and Concrete Composites. 139 (2023) 105050. https://doi.org/10.1016/j.cemconcomp.2023.105050.

[40] A. Pinel, Y. Jorand, C. Olagnon, A. Charlot, E. Fleury, Towards poured earth construction mimicking cement solidification: demonstration of feasibility via a biosourced polymer, Materials and Structures. 50 (2017) 1-17. https://doi.org/10.1617/s11527-017-1092-9

[41] C.M. Ouellet-Plamondon, G. Habert, Self-compacted clay based concrete (SCCC): proof-of-concept, Journal of Cleaner Production. 117 (2016) 160-168. https://doi.org/10.1016/j.jclepro.2015.12.048

[42] G. Landrou, Developement of Self-Compacting Clay Concrete, ETH Zurich, 2018.

[43] S.J. Armistead, A.E. Rawlings, C.C. Smith, S.S. Staniland, Biopolymer Stabilization/Solidification of Soils: A Rapid, Micro-Macro, Cross-Disciplinary Approach, Environ. Sci. Technol. 54 (2020) 13963-13972. https://doi.org/10.1021/acs.est.0c02001

[44] S. Amziane, I. Merta, J. Page, eds., Bio-Based Building Materials: Proceedings of ICBBM 2023, Springer Nature Switzerland, Cham, 2023. https://doi.org/10.1007/978-3-031-33465-8

[45] J. Tourtelot, A. Bourgès, E. Keita, Influence of Biopolymers on the Mechanical Behavior of Earth-Based Building Materials, Recent Progress in Materials. 3 (2021). https://doi.org/10.21926/rpm.2103031

[46] J. Tourtelot, J.-B. D'Espinose De Lacaillerie, M. Duc, J.-D. Mertz, A. Bourges, E. Keita, Strengthening mechanisms of clay building materials by starch, Construction and Building Materials. (2023). https://doi.org/10.1016/j.conbuildmat.2023.133215

[47] M. Gomaa, W. Jabi, A.V. Reyes, V. Soebarto, 3D printing system for earth-based construction: Case study of cob, Automation in Construction. 124 (2021) 103577. https://doi.org/10.1016/j.autcon.2021.103577

[48] C. Ming, A. Mirjan, J. Medina Ibáñez, F. Gramazio, M. Kohler, Impact Printing, 3D Printing and Additive Manufacturing. 9 (2022) 203-211. https://doi.org/10.1089/3dp.2021.0068

[49] A. Carrobé, L. Rincón, I. Martorell, Thermal monitoring and simulation of earthen buildings. A review, Energies. 14 (2021) 2080. https://doi.org/10.3390/en14082080

[50] A. Hakimi, N. Yamani, H. Ouissi, Rapport: Résultats d'essais de résistance mécanique sur échantillon de terre comprimée, Materials and Structures. 29 (1996) 600-608. https://doi.org/10.1007/BF02485967