Research Programme
Doctoral Program in Urban and Regional Development (XXXVIIth cycle)

Experimental, Numerical, and Full-Scale Assessment of Hemp-Lime and Confined Recycled Aggregates for Load-Bearing Feasibility in Architecture

Multiscale Structural Characterisation of Sustainable Materials.

Arthur Bohn

* * * * * *

Supervisor
Prof. Andrea Bocco

Doctoral Examination Committee
Prof. Sofiane Amziane, Université Clermont Auvergne, France
Prof. Patrick Borer, Centre for Alternative Technology, United Kingdom
Prof. Naima Boumediene, Referee, Université de Picardie Jules Verne, France
Prof. Alessia Monaco, Politecnico di Torino, Italy
Prof. Paulien Strandberg-De Bruijn, Referee, Lund University, Sweden

SYNTHESIS

Politecnico di Torino
September, 10th 2025

Synthesis

In the context of rapid construction and increasing environmental constraints, this research focuses on low-impact technologies as innovations rooted in traditional building culture, due to their reliance on bio sourced or reused materials and the use of slow, craft-based techniques, offering potential structural substitutes for conventional construction systems. However, assessing their performance remains a challenge, particularly in bridging experimental and numerical approaches.

This study investigates the potentials of bio-based materials and some of their relative technics. Today the conventional materials for construction field are represented by concrete, fired masonry and steel. However, their global warming potentials are very high and problematic. Finding alternatives in bio-based materials could decrease the emissions of GHG during the process of production by sinking into buildings the atmospheric carbon dioxide.

Vernacular housing of a local territory is one of the main losses as a heritage. In Italy, and more particularly in Piedmont, modern building construction techniques are mostly made of concrete produced by multinational companies. However, many technical issues can be solved by traditional habits. Nevertheless nowadays, beware of global heating, and energy saving in the building sector, this heritage is being abandoned for more efficient and technological solutions which, in turn, have a high environmental impact. The research focuses on low-impact technologies that can be regarded as innovations rooted in traditional building culture, due to their reliance on bio-sourced or reused materials and the use of slow, craft-based techniques. Consequently, in a context of ecological transition where the building sector is expected to undergo significant transformation, architectural research faces the imperative to conceive in a novel manner, characterised by reduced resource consumption, reduced energy usage, increased reuse, and the incorporation of bio-based materials. Despite the clarity of these objectives, the implementation of these concepts is often confronted by the complexity of existing construction realities, and the integration of unconventional materials as structural elements remains a challenge.

As far as possible, this research therefore aims to demonstrate the technical, reproducible attributes that can be recognised in such non-conventional materials. Accordingly, the present work proposes the hypothesis that two materials with low environmental impacts have the potential to be used in the construction of load bearing structures and investigates this hypothesis through a deliberate experimental approach that integrates scientific analysis, numerical modelling, and empirical testing on full scale.

The choice of this research stands that the alignment of different alternative and ecological construction techniques is hardly ever carried out. There is a lot of research based on a single composition or technique, but it does not communicate directly with each other. Here, the choice was made to offer the same attention to all stages of research on both of these two non-conventional low impact technologies.

This research contributes to several key areas in the field of sustainable construction and architectural experimentation. In the development of non-destructive full-scale evaluation methods, it expands the range of analytical tools available for alternative materials. In the articulation between physical experimentation and numerical modelling, the study enhances our understanding of the limitations and application conditions of digital tools when used in non-standardised frameworks. Regarding the full-scale validation of alternative construction systems, this research connects theoretical studies and real-world construction conditions, and this is a type of empirical contribution that remains quite rare in the academic context.

The study focuses on two materials: a bio-sourced composite (hemp-lime) compatible with wet construction methods, and confined recycled aggregates (CRA) used in dry, reuse-based applications. Two main objectives are pursued: first, to examine the mechanical properties of various hemp-lime mixtures for structural applications; second, to evaluate the feasibility of using CRA in foundation systems by measuring resulting settlements. This entire research is based on a cross-experimental methodology that integrates different complementary approaches to investigate the mechanical behaviour of hemp-lime composites and modelling confined recycled aggregates structures.

For hemp-lime, a cross-disciplinary approach integrating laboratory experiments and a scale model was employed to investigate the relationship between the internal thermo-hygrometric conditions, its carbonation process, and its mechanical strength. As the first element studied here, hemp-lime is a combination that offers multiple advantages for sustainable development, human health, and indoor comfort. Its thermal properties and ability to regulate moisture make it an effective solution for reducing energy consumption for heating. Consequently, hemp-lime is gaining popularity in construction, primarily due to its excellent insulating properties.

For CRA, results from a full-scale prototype subjected to loading were compared with digital simulations using two open-source tools: OpenFOAM (FEM) and LIGGGHTS (DEM). Despite their marked differences in terms of nature, implementation, and scientific framework, these two cases are unified by a shared objective: to assess the structural feasibility of materials with low environmental impact under conditions realised within real experiments. By integrating theoretical models, laboratory experiments, and field tests, this research aims to inform a critical evaluation of the validity and limitations of contemporary architectural design tools within the context of low impact technology in sustainable construction.

In accordance with this explanation, the initial case examined is that of hemp-lime, a bio-sourced material that has received significant acclaim for its environmental benefits. However, it has not been determined to be structurally stable yet. Here the method involves a critical bibliographic review aimed at identifying additives that may improve the mechanical performance of hemp-lime materials. The second phase consists of laboratory-scale experimentation on samples. These tests are designed to evaluate mechanical responses and explore correlations between carbonation and strength. Promising additives were selected for testing on samples, while a commercial binder has been used for full-scale prototype. The outcomes of these tests serve as a basis for subsequent non-destructive analysis of this low pointed arch prototype. However, the collapse of the prototype occurred shortly after its completion, highlighting the limitations not only of the material itself but also of the processes involved in its implementation and binder hydration. This incident underscored the disparities between the predicted performance and the actual results in construction, leading to further investigation of the relationship between theoretical predictions and practical applications in this field.

As explained before, a key challenge remains in determining whether certain hemp-lime mixtures can support external loads. The contribution of this research, in particular on the theme of the load-bearing behaviour of hemp-lime, concerns the possibility that certain hemp-lime mixes can exhibit stable mechanical behaviour that is sufficiently resistant not only to withstand their own weight, but also to bear external loads. With this in mind, and with the aim of proposing a structural alternative, the idea to build an entirely compression vault seems coming naturally. Moreover, the honourable architect David Lea had already built a low-pointed arch that wonderfully showcased the mechanical prowess that a mixture of lime and Roman cement could offer. Here, the challenge was to increase the size of the pointed arch, but also to modify its geometric generation so as to integrate all the compression forces within the inner third of the material and thus avoid any traction or bending moment compromising the mechanical performance of the mixture. The technical prowess of the arch enabled us to design the programme for monitoring temperature and internal humidity conditions throughout the construction period.

At the same time, in order to be able to correlate the internal conditions of the low-pointed arch and the mechanical strength values, new air lime-based mixes have been produced on what has already been done in the past in an attempt to achieve more encouraging results (we will see later that the results obtained do not live up to the objective set at the outset). One of the points of the research is therefore to observe an experimental campaign through a critical assessment of the influence, in terms of mechanical behaviour, of several additives incorporated into air lime. The results are also compared to another type of hemp-lime mixture, made with hydraulic lime (NHL5). Unlike concrete, lime hardens over a much longer period and follows a different progression from conventional concrete, which typically reaches its mechanical strength after approximately 28 days. Given this, the tests were conducted over a period extending up to 19 months for the oldest samples. The initial research plan envisaged an equal timeline for all samples; however, results could not be obtained from all samples, as the curing of some was not completed for time management and resources. Only the samples that provided satisfying results are presented here. Nevertheless, the overall campaign demonstrates a high level of robustness in the obtained values, as three samples were tested at each curing time. Consequently, the campaign is based on a total of 99 valid samples.

By utilising the carbonation data from the pointed arch prototype and integrating it into the established correlations between carbonation and compressive strength, we could effectively extrapolate the mechanical strength properties of the arch. This approach also allows us to gain insights into how internal parameters such as temperature and water content, influenced by external conditions, evolve throughout the hardening process. In this context, it is valuable to compare this study with the work conducted by the company Cure, which specializes in determining the hardening phases of concrete through embedded probes in the mix during casting.

In the context of sample-based research, the primary findings on the hemp-lime demonstrate congruence with scientific literature. The hydraulic base sample demonstrates enhanced resistance in comparison to the samples composed of putty lime, excepted the pozzolan and quicklime mixture, likely due to increased hydraulicity induced by the quicklime. These results point to the relevance of further chemical analysis to optimize self-supporting, low-impact construction materials.

The second case refers to a construction system using gabions filled with recycled demolition aggregates, based on the principle of dry reuse. The methodological framework presents two stages simultaneously, involving the use of open-source numerical modelling tools (particularly through DEM and FEM softwares), to simulate the behaviour of gabion structures filled with reused materials, and testing of a full-scale prototype. Therefore, the present study proposes the construction of a digital model, with the intention of comparing it to the results of an experimental study in which the effects of a known load on the stability of the structure are measured. These simulations include analyses of load-bearing behaviour, force chains, settlements, and deformation patterns, and are later compared with data collected during full-scale testing.

The aim of simulating an enclosed system of aggregates in this research is to propose a synthetic and simplified simulation method, while ensuring that the results align with the experimental data measured on the other full-scale pavilion. In order to develop such a model, it is crucial, first, to understand how a Confined Recycled Aggregates (or CRA) can be mathematically defined. The challenge lies in understanding the relationship between forces and deformations or settlements. The challenge is to understand how stresses and strains are related by comparing them with actual results obtained by direct measurement on the fullscale pavilion.

The connection between the loads and the stress field is explained by the equilibrium equations, like the Cauchy equations in the simplest case. Deformations are represented by another state variable, strain, with geometric equations linking displacements and the strain field. Stress and strain are connected through the material's constitutive equations, which provide all the necessary details about the material's mechanical properties. The first research by Professor K. Bagi, published in 1996, provides a microstructural analytical definition of the stress and strain tensors for a granular assembly, aiming to construct a constitutive equation linking forces and deformations. Then, in 2009, the research incorporated particle rotation during contact interactions, and the study relied on a numerical method using finite elements, computed on a computer. Ten years later, Professor Brocato's research focused on a bonded masonry model. This concept arose from the fact that the metal cage allowed very little movement between the elements, and each load was counteracted by a distributed stress across the entire matrix. Moreover, the system upon which the results are based does not consist of spherical particles, but rather polyhedrons. This choice stems from the need to determine in a unique system axis, tensors for each particle over time. In contrast, the polyhedron contains three known and constant tensor axes over time, as they are intrinsically linked.

The modest scientific contribution of this research lies in the practicality of numerical calculation. The goal is not to challenge the constitutive laws or the physical assumptions from the field of physics, but rather to translate into a source code a physical model constructed first, aiming to replicate its deformation results. This research will evaluate the accuracy of the results from two open-source software packages developed by different scientific communities. The method of finite element volumes will be explored using OpenFOAM, which primarily governs the field of fluid dynamics, and the discrete element method will be examined through the use of LIGGGHTS. These two computational engines could provide an efficient means to calculate deformation and load transfer that occur in a granular system, such as confined recycled aggregates.

The CRA technology has proven its viability as a technological element in the field of foundation construction, despite the absence of Italian standards. FEM simulations did not yield satisfactory results in terms of the overall mechanical behaviour of the CRA. Conversely, the DEM allowed granular-level representation, thereby significantly reducing the computational demands. This finding yielded settlements values close to real measurements (5 mm in simulation vs 7-17 mm in reality). These findings are encouraging, as they suggest that the DEM numerical simulation could serve as a viable approach for the design and validation of CRA. These findings suggest enhancement of the DEM Model code by opensource collaboration, as CRA presents a viable alternative to the prevalent use of reinforced concrete as the standard solution in Italy.

In both cases, the final phase which is the full-scale prototype testing hemp-lime and recycled gabions respectively equipped with embedded sensors, and settlement markers. Tests and monitoring are performed on these prototypes, enabling a detailed comparison between the modelled predictions, laboratory data, and the actual structural response observed under realistic conditions. This comprehensive, multi-scalar approach allows for a robust evaluation of the material's performance and the reliability of the predictive models. The different projects required many hours of anticipation, management, design and construction, which is why it took almost two years to obtain the stage that enabled the themes researched in these case studies to be explored.