Scientific Papers. Series E. Land Reclamation, Earth Observation & Surveying, Environmental Engineering. Vol. XIV, 2025
Print ISSN 2285-6064, CD-ROM ISSN 2285-6072, Online ISSN 2393-5138, ISSN-L 2285-6064

INTEGRATING VEGETABLE WASTE IN CLAY COMPOSITIONS: A SUSTAINABLE PATH FOR ECO CONSTRUCTION

Aurelia BRADU[1], Alexandrina-Elena ANDON[1], Alexandra-Marina BARBU[1], Claudiu-Sorin DRAGOMIR[1, 2]

[1]National Institute for Research and Development in Construction, Urban Planning and Sustainable Spatial Development – URBAN-INCERC, 266 Pantelimon Road, District 2, 021652, Bucharest, Romania
[2]University of Agronomic Sciences and Veterinary Medicine of Bucharest, 59 Mărăști Blvd, District 1, 011464, Bucharest, Romania

Corresponding author email: aurelia.bradu@incd.ro

Abstract

Since the dawn of industrialization, technological advancements have progressed rapidly, outpacing the planet`s natural resources` ability to sustain them. In the face of global warming, habitat destruction the imperative to invest in sustainable development practices has become increasingly evident. Clay-based construction materials are gaining traction at the national level, with their benefits recognized for the technical advantages and their contribution to the long-term durability of construction elements. The issue of vegetable waste is a large-scale, multifaceted challenge that continues to grow in urgency alongside rising consumption. Integrating vegetable waste into clay compositions exemplifies how traditional materials can be innovatively adapted to meet contemporary challenges. By combining ancient building techniques with modern knowledge and technology, clay composites can pave the way for a greener construction industry. This sustainable solution not only addresses pressing environmental concerns but also fosters a circular economy where waste becomes a resource. Through such practices, the construction industry can evolve into a model of resilience and sustainability for other sectors to follow.

***Key words**: clay composite, sustainable development, vegetable waste.*

INTRODUCTION

Since the beginnings of industrialization, technological advances have progressed rapidly, exceeding the planet's natural resource capacity to sustain them. If modern society, in its industrial phase, was a production-based society, today, on a global scale, we live in a consumer society. The late 1970s marked the start of the hyper-consumption era, associated with the significant development of capitalist economies, which operate in an economy driven by the continuous and aggressive stimulation of demand, the constant creation of new and often unjustified needs, and the excessive consumption of goods and services. This has led to multiple social and environmental problems (Popescu et al., 2010).
In this context, an essential condition for the sustainable development of modern human society is the need to promote and develop sustainable production and consumption, adapted to the requirements of ecological resource management and environmental preservation (Geissdoerfer et al., 2017).
According to data published by the National Institute of Statistics, agriculture accounted for approximately 5% of Romania’s GDP in 2022, generating over 60% of the total municipal waste in the form of plant waste (Hegyi et al., 2023). The issue of waste, seen in its entirety, is complex and large-scale, becoming increasingly strident as consumption continues to rise. These biodegradable wastes contribute, through their decomposition, to the emission of greenhouse gases, such as methane, further exacerbating climate change (Lachheb et al., 2023). The reuse of these materials in construction can significantly reduce their environmental impact (Cobzaru et al., 2017).

MATERIALS AND METHODS

In the presented study are described five types of recipes, based on matrices of clay, lime, sand, and cement, with plant-based materials (such as straw) incorporated into each. These formulations were designed to create composite materials with improved properties by utilizing sustainable, locally sourced resources. The specific compositions of the clay, lime, sand, and cement matrices used in each formulation are presented in Table 1.

Table 1. The composition of the clay, lime, sand, and cement matrices

Materials	Indicative	R1	R2	R3	R4	R5
Clay	A	10 kg	7 kg	4 kg	13 kg	16 kg
Lime	V	20 kg	26 kg	32 kg	14 kg	8 kg
Sand	N	5 kg	3.5 kg	2 kg	6.5 kg	8 kg
cement	CI	5 kg	3.5 kg	2 kg	6.5 kg	2 kg
Straw	P	2 kg	2 kg	2 kg	2 kg	2 kg
Water	A	8l	8l	8l	8l	8l

The compositions of the different recipes are as follows:

- *Recipe R1* contains 50% lime and 50% of a mixture of clay, sand, and cement;
- *Recipe R2* contains 65% lime and 35% of a mixture of clay, sand, and cement;
- *Recipe R3* contains 80% lime and 20% of a mixture of clay, sand, and cement;
- *Recipe R4* contains 35% lime and 65% of a mixture of clay, sand, and cement;
- *Recipe R5* contains 20% lime and 80% of a mixture of clay, sand, and cement.

These formulations were designed to balance the mechanical properties of the materials with sustainable practices by incorporating agricultural residues such as straw, thereby reducing environmental impact while enhancing the thermal and structural performance of construction materials. Each of the recipes varied in terms of the lime-to-clay ratio, which influences the material's strength and thermal conductivity.

Straw, generated in significant quantities from wheat production (with Romania ranking 4th in the EU in this regard), represents an available resource, with millions of tons produced annually. Straw-light clay is a mixture of straw and clay with a density of less than 1200 kg/m^3, (Azzolino et al., 2020). This density is considered optimal for light clay with straw, providing a good balance between thermal insulation and material strength. The mixture allows for efficient insulation and adequate compressive strength, preventing deformation and loss of thermal properties (Petcu et al, 2023). If the density exceeds 1200 kg/m^3, it is referred to as clay with straw. The resulting material is denser, stronger, with reduced insulating properties, and becomes heavier and harder to handle during construction.

Elements with densities under 600 kg/m^3 are not recommended because the resulting material would be too fragile and prone to sedimentation and rot of the straw due to moisture infiltration. In this case, the straw is more vulnerable to microbial attacks and pests (such as wood lice), which can affect durability (Tavakoli, 2015).

Although studies have been conducted on selecting the appropriate types of straw, more important than the type of straw is the structure of the nodes (Figure 1).

Figure 1. The structure of the nodes in wheat straw

Straws with rigid nodes are preferred to increase thermal insulation because they do not deform easily and keep the air trapped inside, prevent excessive compaction of the clay-straw mixture, as these do not easily deform under the weight of the clay (Barone et al., 2011). This improves the durability and thermal insulation properties of the material. They also contain cellulose and lignin, which reinforce the plant stem's structure. These components are resistant and help protect against rot and degradation under the influence of moisture. At the same time, lignin provides resistance and structural durability. As the plant matures, the lignin in the nodes becomes more concentrated, further strengthening the node structure and giving an advantage to older straws, which are better suited for construction.

The length of the straw should not exceed the thickness of the elements. The straw can be cut by various mechanical methods (with specialized machines or shredders) or manually (with scissors or other tools).

Adding straw to the mixture can significantly reduce the shrinkage of the clay. Since the fibers increase the bonding strength of the mixture, cracks are minimized. To avoid the internal rotting of the straw, fungal growth, and to reduce shrinkage, clay elements with straw additions are recommended to have a thickness of less than 25 cm (Minke, 2000).

The workability of the clay composite can be improved by additives. The shrinkage process is influenced by the amount of sand or other large aggregates, the water content, the types and amounts of clay minerals, the distribution of the granulation of the aggregates (Calatan et al., 2020). The analysis of the clay's composition can be performed through a series of field tests (Carraro et al., 2021), such as water content test, sedimentation test, and ball throwing test, as well as laboratory conditions: Atterberg plasticity test, Proctor compaction test, and drying shrinkage test.

The addition of chopped straw contributes to increasing the bonding strength of the mixture, reducing the appearance of cracks (Figure 2 and Figure 3).

Figure 2. The introduction of straw into the composition

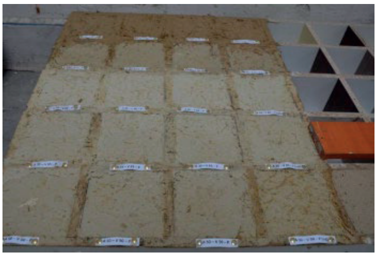

Figure 3. Casting of the samples

To enhance stability, straw is incorporated into the composition using a mechanical mixing process. The stabilizers coat the clay minerals, preventing water infiltration and minimizing volumetric changes.

Water resistance can be increased by altering the distribution of the earth and sand granulation. The straw bale technology (Minke, 2000) involves placing straw bales on the foundation and covering them with a layer of clay. This protects the straw from moisture and helps improve thermal insulation. The technology is fast and efficient, and the straw bales provide a stable frame and good protection against extreme temperatures.

The "Clay-Straw" technology (Goodhew & Griffiths, 2005) involves mixing straw with clay to produce a composite mass used for manufacturing tiles or panels. These elements are dried and subsequently installed on-site. This technology enables the rapid construction of walls while providing a user-friendly material with good thermal performance.

The "Tuf with Straw" technology combines tuff with straw to produce a lightweight yet strong construction material (Belayachi et al., 2016). The tuff helps stabilize the structure, and the straw improves flexibility and insulation. The structured elements are then assembled on-site and protected with a layer of clay or other materials to make them more durable.

The "Rammed Earth with Fibers" technology involves combining raw clay with fibers such as straw or hemp, which are then compacted within a mold to construct solid walls (Tesoro et al., 2021). Although traditional rammed earth technology uses earth without fibers, adding fibers increases flexibility and crack resistance. The clay is mixed with sand and fibers to create a more durable and elastic material. Water is added to help form the mixture. The clay-fiber mixture is placed into a mold and compacted with a hammer or a mechanical device to ensure density. The wall is built layer by layer, with each layer being compacted to increase its density and strength. Controlled drying helps achieve solid and durable walls.

The "Adobe" technology involves mixing unbaked clay blocks with fibers to improve cohesion and strength (Illampas et al., 2009). The blocks are poured into moulds and left to dry in the sun, then used to build self-supporting walls. This is a traditional and cost-effective construction method, with reduced costs. Adobe blocks have excellent insulation properties and are resistant to extreme temperatures. The cement addition aims increase the compressive strength, improve mechanical performance and durability of the traditional material without compromising thermal insulation properties. Cement reduces porosity and improves water resistance, making the material less susceptible to cracking and deformation under load while providing protection against environmental factors such as moisture and temperature fluctuations. The use of cement in unburned clay with straw elements must be well calculated so as not to decrease the thermal performance of the material (Mircea et al., 2021). Too much cement quantity can reduce the insulating capacity of the straw, which could negatively affect the energy efficiency of the construction. The ideal is to find an optimal balance between straw, clay, and cement to achieve a strong and durable material with good thermal properties.

RESULTS AND DISCUSSIONS

The behaviour of composite thermal insulation materials based on plant fibers in a clay-lime matrix has been studied by performing the following measurements at the material level, in accordance with the laboratory procedures and relevant standards (Bailly et al., 2024; Zhao et al., 2021).

The linear dimensions were determined using a caliper with an accuracy of 0.01 mm, densities of samples dried at 80°C were measured using the gravimetric method, mass was determined using a balance, thermal conductivity, and thermal resistance of samples dried at 80°C were evaluated using the thermofluxmetric method.

Finally, the compressive strength was measured by applying a uniformly distributed load to the samples, which was gradually increased until rupture (Table 2, Figure 4 and Figure 5).

All these procedures allow for a comprehensive characterization of materials and a detailed understanding of their mechanical and thermal performance.

Together, these detailed measurements allow for a complete picture of the physical-mechanical characteristics of the material to be obtained for determining its suitable applications in sustainable and energy-efficient constructions. They are also suitable and for selecting the optimal material for the specific conditions of the project and ensuring a balance between mechanical performance and thermal efficiency.

Table 2. Maximum load at failure and compressive strength

Recipe	Length (mm)	Width (mm)	Thickness (mm)	Area (mm^2)	F (kN)	f_b (N/mm^2)
R1	145.6	146.36	146.35	21,308	18.1	0.85
R2	146.64	145.47	147.33	21,332	13.7	0.64
R3	145.29	148.3	143.73	21,548	13.3	0.62
R4	145.32	147.27	146.88	21,401	14.8	0.69
R5	146.88	145.96	146.6	21,581	16.1	0.75

Figure 4. Testing of R2 samples

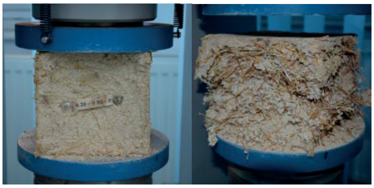

Figure 5. Testing of R3 samples

The data from Table 2 shows that the maximum load at failure (F) and compressive strength (f_b) vary depending on the recipe, with compressive strength values ranging between 0.62 and 0.85 N/mm², indicating differences in the structure and mechanical behaviour of the tested materials. These differences can be attributed to the variability of the ingredients in the composition of each recipe, which directly influences the material's structure, mechanical behaviour, and stability against environmental factors.

Recipe with 50% lime and 50% of clay, sand and cement mixture shows the best compressive strength, indicating superior mechanical performance, while recipe with 80% lime and 20% of clay, sand and cement mixture has the lowest strength, which could impact its use in demanding structural applications.

Data from Table 3 highlight significant variations in thermal conductivity (0.1332-0.2306 W/mK) and thermal resistance (0.27-

0.46 m^2K/W), suggesting that certain recipes are more efficient in thermal insulation than others. Recipe with 80% lime and 20% clay, sand, and cement mixture shows the best performance as a thermal insulator, while recipe with 20% lime and 80% clay, sand, and cement mixture is the least efficient in this regard.

Table 3. Thermal conductivity and thermal resistance

Recipe	Thickness (m)	Thermal conductivity (W/mK)		Thermal resistance (m^2K/W)	
R1	0.0625	0.1577	0.1535	0.40	0.41
R2	0.0636	0.1492	0.1453	0.43	0.44
R3	0.0610	0.1369	0.1332	0.45	0.46
R4	0.0615	0.1742	0.1696	0.35	0.36
R5	0.0623	0.2368	0.2306	0.26	0.27

Recipes with lower conductivity have higher thermal resistance, making them more suitable for applications where thermal insulation is important.

The results suggest that higher lime content enhances thermal resistance, while higher cement content improves mechanical strength. The key takeaway is that a moderate use of lime and cement allows for a balance between durability and environmental sustainability.

The studied recipes may represent an excellent option for sustainable and eco-friendly construction, with improvements in both mechanical and thermal performance. However, using this mixture requires a balance between ecological advantages and technical requirements, with particular attention to the materials used and their environmental impact. A moderate use of cement and lime can help achieve a balance between durability, performance, and ecology.

CONCLUSIONS

The mixture containing 50% lime and 50% clay, sand, and cement demonstrated the best mechanical performance, while the mixture with 80% lime and 20% clay, sand, and cement provided the best thermal insulation. The selection of the appropriate material depends on the intended application: for high mechanical strength, the 50% lime and 50% clay, sand, and cement mixture is the optimal choice, whereas for enhanced thermal insulation, the 80% lime and 20% clay, sand, and cement mixture is preferable.

To enable the creation of new domestic products and methodologies, with lower costs compared to imports, targeting the balance between accessibility, cost, performance, durability, and optimizing insulating materials composed of renewable raw material resources, further experimental research is needed, either in the laboratory or on-site, to provide new insights regarding the maintenance of thermal, mechanical, and hygroscopic characteristics over time.

ACKNOWLEDGEMENTS

This paper was supported by the Program Advanced research on the development of eco-innovative solutions, composite materials, technologies and services, in the concept of a circular economy and increased quality of life, for a sustainable digitized infrastructure in a built and urban environment resilient to climate change and disasters, “ECODIGICONS”, Program code: PN 23 35 03 01: “Integrated system of development and scientific research of constructions and vital infrastructures exposed to extreme seismic and climatic environmental actions and the exploitation of sustainable resources of materials and energy”, financed by the Romanian Government.

REFERENCES

Azzolino, C., Macrì, M., & Mancuso, S. (2020). Straw Buildings: A Good Compromise between Environmental Sustainability and Energy-Economic Savings. *Applied Sciences, 10*(12), 4361-4378.

Bailly, G. C., El Mendili, Y., Konin, A., Khoury, & E. (2024). Advancing Earth-Based Construction: A Comprehensive Revw of Stabilization and Reinforcement Techniques for Adobe and Compressed Earth Blocks. *Engineering, 5*(2), 750-783.

Barone, J., & Kuehling, R. (2011). *Building with Straw Bales: A Handbook for Designers and Builders.* Earthscan, 50-70.

Belayachi, N., Bederina, M., Makhloufi, Z., Dheilly, R. M., Montrelay, N., & Queneudec, M. (2016). Contribution to the development of a sand concrete lightened by the addition of barley straws. *Construction and Building Materials, 113*, 513-522.

Calatan, G., Hegyi, A., Dico, C., & Szilagyi, H. (2020). Opportunities regarding the use of adobe-bricks within contemporary architecture. *Procedia Manufacturing*, *46*, 150-157

Carraro, A., Fauchille, A., Di Filippo, E., Kotronis, P., & Sciarra, G. (2021). A Review of Sand-Clay Mixture and Soil-Structure Interface. *Geotechnics, 1*(1), 12-34.

Cobzaru, A., Cherecheș, M., & Ciobanu, A. (2017). *Cercetări experimentale pentru creșterea performanței materialelor de construcții: 2010-2017.* Editura INCD - URBAN-INCERC.

Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2017). The Circular Economy - A new sustainability paradigm. *Journal of Cleaner Production*, *143*, 757-768.

Goodhew, S., & Griffiths, R. (2005). Sustainable earth walls to meet the building regulations. *Energy and Buildings, 37*, 451-459.

Hegyi, A., Petcu, C., Ciobanu, A. A., Calatan, G., & Bradu, A. (2023). Development of Clay-Composite Plasters Integrating Industrial Waste. *Materials*, *16*(14), 4903

Illampas, R., Ioannou, I., & Charmpis, D. C. (2009). Adobe: An Environmentally Friendly Construction Material. *WIT Transactions on Ecology and the Environment*, 120, 245-256.

Lachheb, H., Bencheikh, A., & Bouhicha, M. (2023). Sustainable construction with unburnt clay bricks reinforced with agricultural residues. *Civil and Environmental Engineering Journal*, 1-12.

Minke, G. (2000). *Building with Earth: A Handbook,* Birkhäuser Verlag, 120-150.

Mircea, C., Toader, T.-P., Hegyi, A., Ionescu, B.-A., & Mircea, A. (2021). Early Age Sealing Capacity of Structural Mortar with Integral Crystalline. *Materials, 14*(2), 348-358.

Petcu, C., Dobrescu, C. F., Dragomir, C. S., Ciobanu, A. A., Lăzărescu, A. V., & Hegyi, A. (2023). Thermophysical Characteristics of Clay for Efficient Rammed Earth Wall Construction. *Materials*, *16*(17), 6015.

Popescu, C., Popescu S.-F., & Stroe C. (2010), Consumul din perspectiva împlinirii vieţii umane, *Amfiteatrul Economic*, *vol. XII*, nr. 28, 529-544

Tavakoli, H. (2015). Straw Bale Construction: A Practical Guide for the UK. *The Crowood Press*, 45-95.

Tesoro, M., Falcicchio, C., & Foti, D. (2021). Rammed Earth with Straw Fibers and Earth Mortar: Mix Design and Mechanical Characteristics Determination. *Fibers*, *9*(5), 30.

Zhao, L., Li, J., & Zhang, S. (2021). Effect of fiber addition on the mechanical properties of unfired clay bricks. *Journal of Building Materials*, *23*(7), 1234-1245.