# REDUCING THE CARBON FOOTPRINT IN THE CONSTRUCTION SECTOR BY REPLACING CERAMIC BRICKS WITH ALTERNATIVE MATERIALS

Lubomir Tashkov[1], Penka Zlateva[1], Nina Penkova[2]

[1]*Technical University of Varna*
*Department of Thermal Engineering*
*1 Studentska St., 9010 Varna, Bulgaria*
[2]*University of Chemical Technology and Metallurgy*
*8 Kliment Ohridski Blvd., Sofia1797, Bulgaria*
*E-mail: pzlateva@tu-varna.bg*

*Received 12 December 2023*
*Accepted 23 July 2024*
*DOI: 10.59957/jctm.v59.i6.2024.9*

## ABSTRACT

*The use of non-fired materials with additives of vegetable waste instead of traditional building ceramics reduces the energy input and the carbon footprint in the construction sector. This applies to one- and two-story buildings due to the lower load-bearing capacity of non-fired bricks.*

*A possibility for substitution of the fired ceramics with non-fired clay bricks with additives of straw at the building of the walls of a single-family house is analyzed. The subsequent reductions of the embodied energy, carbon dioxide, and thermal losses of the buildings are determined.*

*Keywords: building ceramic, non-fired clay, plant additives, green construction, embodied energy, embodied carbon.*

## INTRODUCTION

The development of modern civilization and the increasing needs for residential and public buildings pose a challenge for researchers and engineers to look for eco-friendly and sustainable building materials [1, 2]. Traditional ceramics have been a longstanding choice for construction due to their reliable qualities. However, they are associated with high embodied energy and significant carbon emissions at their manufacturing [2, 3]. Scientific advancements in this field are of paramount importance for the transition to more sustainable and environmentally friendly construction, considering the global climate challenges. Such innovations can offer additional economic benefits while simultaneously reduce wastes and increase the use of resource-efficient materials [4].

The substitution of conventional building materials with alternative ones is a topic of fundamental importance in the fields of civil engineering and materials science. This approach is based on the quest for innovative materials that not only fulfill the necessary functions for constructing buildings and infrastructure, but also have a minimal impact on the environment [5, 6].

An essential benefit of transitioning from traditional building materials such as fired ceramics to alternatives, loads to a reduction of the energy footprint within the construction process. The firing of the ceramic bricks necessitates relatively high temperatures, energy input and carbon dioxide emissions [7, 8]. Their current substitution initiative endeavors to incorporate materials that exhibit reduced embodied energy while preserving the requisite durability and functionality essential for construction applications [9].

Before being adopted as alternatives, new building materials undergo thorough scientific research and analysis of their thermo-physical and mechanical properties. These analyses encompass measurements of thermal characteristics, density, mechanical strength and resistance to external influences [10]. Such an approach necessitates the examination and evaluation of various materials, providing comprehensive information about their qualities and applications in the field of construction [11].

In addition to the aspects of material properties, researchers are focusing on the potential for integrating agricultural plant residues into the composition of building materials. This provides opportunities for the utilization of agricultural wastes. The investigations in this context encompass an analysis of the influence of various types of plant residues on the thermal, chemical, and mechanical characteristics of the building materials [12]. That is necessary to validate the potential of plant residues as components of sustainable building materials [13 - 15].

The current study focuses on alternatives to replace traditional building ceramics to reduce the carbon footprint in the construction sector and to incorporate sustainable and innovative solutions.

## EXPERIMENTAL

Diverse structural systems are employed in civil engineering. The most prevalent configurations encompass the following components: a foundation, load-bearing structure and enclosing walls that may be internal or external and serve a non-load-bearing purpose. Conventionally, the foundation and load-bearing structure are composed of reinforced concrete. Fired ceramic elements are typically used in the construction of enclosing non-load-bearing walls.

Certain materials, such as unfired clay bricks, are natural building materials with a history dating back to the dawn of civilization. Nevertheless, scientific scrutiny of their material properties has only emerged in recent decades. Unfired clay bricks are primarily composed of clay, sand and water, with some formulations incorporating additives like clay slip to enhance the final product’s durability [16]. In most cases, locally sourced raw materials are used, often supplemented with various organic materials such as animal manure or plant products [17]. Plant-based additives, such as straw from various grain crops like wheat, oats, barley, industrial hemp, coconut fibers, cornstalks, rice husks, wood shavings and other vegetative species or waste materials, find the most extensive application.

One of the primary characteristics of the building elements is the coefficient of thermal conductivity. It determines the structure’s ability to maintain a comfortable indoor environment shielded from natural elements [18]. Table 1 presents results from studies conducted by different authors [19, 20]. The thermo-physical characteristics vary with the type and quantity of the additives. The thermal conductivity of the

Table 1. Thermal conductivity of non-fired clay bricks with additives.

| № | Additives | Coefficient of thermal conductivity, λ, W $m^{-1}$ $K^{-1}$ | Density, r, kg $m^{-3}$ |
|---|---|---|---|
| 1 | 75 % by wheat straw | 0.186 | 1000 |
| 2 | 50 % by volume wheat straw | 0.249 | 1512 |
| 3 | 25 % by volume wheat straw | 0.308 | 1725 |
| 4 | 75 % by volume barley straw | 0.143 | 876 |
| 5 | 50 % by volume barley straw | 0.219 | 1359 |
| 6 | 25 % by volume barley straw | 0.275 | 1684 |
| 7 | 0,5 % straw | 0.650 | |
| 8 | 1 % straw | 0.625 | |
| 9 | 2 % straw | 0.463 | |
| 10 | 3 % straw | 0.387 | |
| 11 | 4 % straw | 0.337 | |

alternative material is nearly two times lower than the fired ceramics at this density. This is due to the quantity of additives incorporated.

The embodied energy is another important parameter, used in the last decades for life cycle assessment of the buildings and the materials for the construction.

The production of traditional building ceramics can be divided into several main steps: raw materials treatment and mixing, shaping, drying and firing. The thermal energy consumption in brick manufacturing is often supplied by natural gas during the drying and firing processes. Wienerberger Academy presents values for embedded energy in its products [21]:

- 274 kWh ton$^{-1}$ finished products (43 %);
- 360 kWh ton$^{-1}$ finished products (57 %).

Assuming that the unfired bricks are being produced at the steps, mentioned above, excluding the firing, their embodied energy is 360 kWh ton$^{-1}$ lower than the embodied energy of the fired ceramic elements.

## RESULTS AND DISCUSSION

The use of alternative materials for the construction influences on the following:

- thermal transmittance of the exterior building envelopes and the subsequent necessary energies for air conditioning;
- embodied energy of the buildings.

Two options of building walls are analyzed on the design stage of a single-family house in Samokov, Bulgaria to estimate the above parameters: traditional fired ceramic blocks (Variant 1) and alternative unfired ones (Variant 2). Nshimiyimana et al. described the building as featuring a reinforced concrete frame structure [24]. The structural frame, the foundations and the insulating materials are identical at the two options, preserving the overall architectural vision of the building (Fig. 1).

The design of the building specifies that the exterior walls consist of 25 cm Wienerberger ceramic bricks with a total surface area of 230 m² [19]. The external wall surfaces are covered with 12 cm mineral wool, while XPS insulation is used in the foundation area.

The amount of the fired building bricks needed for the construction of external and internal walls was obtained from the architectural project's quantitative assessment (Table 2). The total quantity of bricks required for building the structure is 55.1 tons.

The alternative building components are chosen with a density as close as possible to that of the traditional ceramic blocks. This ensures an equivalent load on the structural system by maintaining the weight of the walls in the building. To achieve the desired density, the amount of additive should be 75 % straw by volume.

The thermal transmittances of the exterior building envelopes are determined following Bulgaria's regulatory requirements [23]:

$$U_w = \frac{1}{R_{SI} + \sum R + R_{SE}} \;, \quad \text{W m}^{-2}\,\text{K}^{-1}; \qquad (1)$$

$$\sum R = \sum_{1}^{n} \frac{\delta_i}{\lambda_1} \;, \quad \text{m}^2\,\text{K W}^{-1}; \qquad (2)$$

Fig. 1. Design of single-family house.

Table 2. Required amounts of bricks for the interior and exterior walls.

| | Area | Volume | Density | Weight | Weight |
|---|---|---|---|---|---|
| | $m^2$ | $m^3$ | kg $m^3$ | kg | ton |
| Bricks 25 cm wide (external walls) | 230 | 57.5 | 750 | 43125 | 43.1 |
| Bricks 12 cm wide (internal walls) | 145 | 17.4 | 690 | 12006 | 12.0 |

Table 3. The structure of exterior walls made by fired ceramics (Variant 1).

| № | Layer | Thickness, cm | Thermal conductivity, W $m^{-1}$ $K^{-1}$ | $R_i$, $m^2$ K $W^{-1}$ |
|---|---|---|---|---|
| 1 | Gypsum plaster | 0.5 | 0.23 | 0.022 |
| 2 | Lime-sand plaster | 1.5 | 0.7 | 0.021 |
| 3 | Lattice masonry of fired bricks | 25 | 0.26 | 0.962 |
| 4 | Styrofoam | 12 | 0.035 | 3.429 |
| 5 | Cement-sand plaster | 1.5 | 0.93 | 0.016 |
| 6 | Mineral plaster | 0.5 | 0.87 | 0.006 |

Table 4. The structure of exterior wall made by unfired bricks with additives of straw (Variant 2).

| № | Layer | Thickness, cm | Thermal conductivity, W $m^{-1}$ $K^{-1}$ | $R_i$, $m^2$ K $W^{-1}$ |
|---|---|---|---|---|
| 1 | Gypsum plaster | 0.5 | 0.23 | 0.022 |
| 2 | Lime-sand plaster | 1.5 | 0.7 | 0.021 |
| 3 | Unfired clay bricks with 75 % by volume barley straw | 25 | 0.14 | 1.786 |
| 4 | Styrofoam | 12 | 0.035 | 3.429 |
| 5 | Cement-sand plaster | 1.5 | 0.93 | 0.016 |
| 6 | Mineral plaster | 0.5 | 0.87 | 0.006 |

where: $R_{si}$ and $R_{se}$ are the resistances of the thermal boundary layers at the internal and the external side of the walls, $m^2$ K $W^{-1}$; $\Sigma R$ is the sum of different layers resistances, $m^2$ K $W^{-1}$; $d_i$ is the layer thickness, m; $\lambda_i$ is the layer thermal conductivity, W $m^{-1}$ $K^{-1}$.

The thermal transmittances of the building walls using traditional fired ceramic (Variant 1) and unfired bricks with straw additives (Variant 2) are determined based on the thicknesses, thermal conductivities and thermal resistances of the layers (Tables 3 and 4):

$U_w$= 0.22 W $m^{-2}$ $K^{-1}$ at Variant 1;

$U_w$= 0.18 W $m^{-2}$ $K^{-1}$ at Variant 2.

The resistances of the boundary layers at the external and the internal side of the walls are assumed to be identical in both variants at equal indoor and outdoor temperatures and conditions: $R_{si}$ = 0.13 m² K $W^{-1}$ and $R_{se}$ = 0.04 m² K $W^{-1}$ [23]. It is noticeable that the thermal transmittance for the wall with alternative elements is 18 % smaller than the fired ceramics wall.

The thermal energy losses through the walls $Q_w$ at the equation can determine one heating period that has to be compensate by the heating systems:

$$Q_w = 0.001.\, U_w.\, F_w.\Delta t.\tau, \text{ kWh year}^{-1} \quad (3)$$

where $F_w$ is the total area of the walls, $m^2$; $\Delta t$ is the average difference between the outer in inner temperatures, K; $\tau$ is the time duration of the hating period of the year, h.

The thermal losses at the two variants of the walls during the heating season with a duration of 5280 h (220 days x 24 h), average outdoor temperature in Samokov of 4.5°C and difference of 15.5 between the outer and inner temperatures are:

Variant 1: $Q_w$ = 4141 kWh year$^{-1}$

Variant 2: $Q_w$ = 3388 kWh year$^{-1}$

The thermal losses of the wall, made by the non-fired bricks with additives are also 18 % smaller as it is expected.

Teixeira et al. described the reduction in embodied energy for the building, depending on the required quantity of bricks, as being proportional to the energy needed for firing [25].

*Embodyed energy= bricks mass [ton] x energy for firing [kWh year$^{-1}$]* (4)

or

*Embodyed energy= 55.1 ton x 360 kWh year$^{-1}$ =19863 kWh*

The reduction of carbon dioxide ($CO_2$) emissions is a critical objective that encompasses a range of strategies and actions aimed at curbing the release of this greenhouse gas into the atmosphere. These efforts are vital to slow down global warming, minimize its adverse effects, and transition towards a more sustainable and environmentally friendly future [25, 26].

The saved embodied $CO_2$ emissions at the alternative Variant 2 of the external walls can be obtained using the reduction of the embodied energy and the coefficient of equivalent emissions per kWh energy $K_{CO2}$ [23]:

$$CO_2 = \text{Embodyed energy [kWh]} \times K_{CO2}, \text{ [kgCO}_2\text{ kWh}^{-1}] \quad (5)$$

Considering that the reduced embodied energy at the non-fired bricks is a thermal energy, supplied by natural gas with $K_{CO2} = 220\ kgCO_2\ kWh^{-1}$.

$$CO_2 = 19863\ kWh \times 0.22\ kgCO_2\ kWh^{-1} = 4370\ kgCO_2 = 4.4\ ton\ CO_2$$

Additional carbon dioxide reduction will be obtained during the technical life of the building due to the reduction of the thermal losses through the external walls at Variant 2. It depends on the type of the primary energy for heating of the building.

## CONCLUSIONS

Alternative building materials based on unfired clay with included plant additives represent a real opportunity to reduce the embodied energy and the carbon footprint in the construction sector. Their manufacturing requires less thermal energy compared to the traditional fired ceramic bricks and allows utilization of agricultural plant wastes.

The walls, made by non-fired building bricks with plant additives have lower thermal transmittance in comparison to the fired building ceramics. That results in higher energy efficiency of the buildings and reduces the energy for heating and cooling. Such differences of 18 % in favor of walls, made by non-fired clay bricks with 75 % straw are established for a single-family house in the present study.

## REFERENCES


1. D.G. Sahlol, E. Elbeltagi, M. El-Zoughiby, M.A. Elrahman, Sustainable building materials assessment and selection using system dynamics, J. Build. Eng., 35, 2020, 101978.
2. M.R. Munaro, S.F. Tavares, L. Bragança, Towards circular and more sustainable buildings: A systematic literature review on the circular economy in the built environment, J. Clean. Prod., 260, 2020, 121134.
3. M. Norouzi, M. Chàfer, L.F. Cabeza, L. Jiménez, D. Boer, Circular economy in the building and construction sector: A scientific evolution analysis, J. Build. Eng., 44, 2021, 102704.
4. Md. U. Hossain, S.T. Ng, P. Antwi-Afari, B. Amor, Circular economy and the construction industry: Existing trends, challenges and prospective framework for sustainable construction, Renew. Sustain. Energy Rev., 130, 2020, 109948.
5. G. Xu, X. Shi, Characteristics and applications of fly ash as a sustainable construction material: A state-of-the-art review, Resour. Conserv. Recycl., 136, 2018, 95-109.
6. N. Kisku, H. Joshi, M. Ansari, S.K. Panda, S. Nayak, S.C. Dutta, A critical review and assessment for usage of recycled aggregate as sustainable construction material, Constr. Build. Mater., 131, 2017, 721-740.
7. R.A.M. Black, B.M. Skinder, Black carbon and other pollutants from brickfields country-wise: Impact

assessment and policy guidance under welfare analysis, Front. Manage. Bus., 4, 1, 2022, 252-262.
8. H. Bal, Y. Jannot, S. Gaye, F. Demeurie, Measurement and modelisation of the thermal conductivity of a wet composite porous medium: Laterite based bricks with millet waste additive, Constr. Build. Mater., 41, 2012, 586-593.
9. M. Ouedraogo, K. Dao, Y. Millogo, J.-E. Aubert, A. Messan, M. Seynou, L. Zerbo, M. Gomina, Physical, thermal and mechanical properties of adobes stabilized with fonio (Digitaria exilis) straw, J. Build. Eng., 23, 2019, 250-258.
10. A. Silva, F. Gaspar, A. Bakatovich, Composite materials of rice husk and reed fibers for thermal insulation plates using sodium silicate as a binder, Sustainability, 15, 2023, 11273.
11. L. Zheng, M. Mueller, C. Luo, T. Menneer, X. Yan, Variations in whole-life carbon emissions of similar buildings in proximity: An analysis of 145 residential properties in Cornwall, UK, Energy Build., 296, 2023, 113387.
12. Z. Sun, Z. Ma, M. Ma, W. Cai, X. Xiang, S. Zhang, M. Chen, L. Chen, Carbon peak and carbon neutrality in the building sector: A bibliometric review, Buildings, 12, 2022, 128.
13. Z. Gao, H. Liu, X. Xu, X. Xiahou, P. Cui, P. Mao, Research progress on carbon emissions of public buildings: A visual analysis and review, Buildings, 13, 2023, 677.
14. Y. Zhang, S. Jiang, D. Quan, K. Fang, B. Wang, Z. Ma, Properties of sustainable earth construction materials: A state-of-the-art review, Sustainability, 16, 2024, 670.
15. G.C. Bailly, Y. El Mendili, A. Konin, E. Khoury, Advancing earth-based construction: A comprehensive review of stabilization and reinforcement techniques for adobe and compressed earth blocks, Eng., 5, 2024, 750-783.
16. M. Lachheb, N. Youssef, Z. Younsi, A comprehensive review of the improvement of the thermal and mechanical properties of unfired clay bricks by incorporating waste materials, Buildings, 13, 2023, 2314.
17. G.C. Bailly, Y. El Mendili, A. Konin, E. Khoury, Advancing earth-based construction: A comprehensive review of stabilization and reinforcement techniques for adobe and compressed earth blocks, Eng, 5, 2024, 750-783.
18. C. Turco, M. Abedi, E. Teixeira, R. Mateus, Thermophysical properties of compressed earth blocks incorporating natural materials, Energies, 17, 2024, 2070.
19. Wienerberger, Energy saving seminar, (n.d.). https://www.wienerberger.com/content/dam/corp/corporate-website/downloads/investors-downloads/2023/20240221-wienerberger-FY-2023-Presentation.pdf (accessed on 19 May 2024).
20. G. Jechkov, Handbook of building ceramics, Techniques, 1986.
21. Regulation No RD-02-20-3 about the technical requirements for the energy performance of buildings, (n.d.), Ministry of Energy of the Republic of Bulgaria, 2022. https://www.me.government.bg/en.
22. B.A. Lejano, R.J. Gabaldon, P.J. Go, C.G. Juan, M. Wong, Compressed earth blocks with powdered green mussel shell as partial binder and pig hair as fiber reinforcement, Int. J. GEOMATE, 16, 2019, 137-143.
23. D. Csanády, O. Fenyvesi, B. Nagy, An empirical model of heat-treated straw bulks' thermal conductivity based on changes in mass and chemical composition, J. Therm. Anal. Calorim., 148, 2023, 3731-3749.
24. P. Nshimiyimana, A. Messan, L. Courard, Physico-mechanical and hygro-thermal properties of compressed earth blocks stabilized with industrial and agro by-product binders, Materials, 13, 2020, 3769.
25. E.R. Teixeira, G. Machado, P. Junior, A. Guarnier, J. Fernandes, S.M. Silva, R. Mateus, Mechanical and thermal performance characterisation of compressed earth blocks, Energies, 13, 2020, 2978.
26. Y. Zhang, A.E. Ghaly, B. Li, Physical properties of wheat straw varieties cultivated under different climatic and soil conditions in three continents, Am. J. Eng. Appl. Sci., 5, 2012, 98-106.