Proceedings of International Structural Engineering and Construction, 8(1), 2021
Interdisciplinary Civil and Construction Engineering Projects
Edited by El Baradei, S., Abodonya, A., Singh, A., and Yazdani, S.

ISSN: 2644-108X
www.doi.org/10.14455/ISEC.2021.8(1).SUS-04

SUSTAINABLE BUILDING PREFABRICATED ELEMENT BASED ON STABILIZED RESIDUAL QUARRY SLUDGE AND ITS HEAT TRANSFER ANALYSIS

ANDRES RESTREPO, NICOLAS ZAPATA, JUAN TORRENEGRA, YHAN ARIAS, and JUAN OCHOA

Architecture Dept, Universidad Nacional de Colombia, Medellín, Colombia

In this work, a prefabricated masonry element is produced by reusing a residual sludge generated by the Colombian mining industry, especially the sandstone quarries. The addition of Ca $(OH)_2$ and NaOH stabilizes this waste. Application of a response surface model results in optimal admixture specifications, achieving improvements in load capacity (8 MPa) and durability according to its dimensional stability, upgrading the traditional techniques. Albeit remains a lack in the study of its thermal behavior. Thus, A heat transfer analysis employing computational simulations based on the Finite Element Method (FEM) is applied to predict the thermal performance of manufactured elements with stabilized quarry sludge (SQS). Besides, several construction materials are simulated, allowing their contrast and the complement between simulation and experimentation, pointing to the achievement of a good performance in different climatic conditions, including actual city case characteristics. It is concluded that according to SQS block thermal performance, it can be a suitable building element candidate. Hence, more sustainable processes in the mining and construction production chain can be achieved.

Keywords: Mining waste, Alkali activated, Masonry brick, Computational simulation.

1 INTRODUCTION

In Colombia the exploitation of the rocky material used in the construction industry stood at 33.033.666 m^3 for 2015; being the sludge generation of 6%, equivalent to 1.982.019 m^3. In some cases, this residue is thrown away in a garbage dump, in other cases is used in the ceramics industry (bricks and tile production), and at worst is thrown away into the hydric sources. Besides, sludge generation can be larger, taking into account the illegal mining processes. The use of $Ca(OH)_2$ for soil stabilization is widely known around the world (Bell 1996), additionally, Na(OH) is used as an alkaline activator to break Si-O and Al-O bonds and form poly-sialates that can reorganize and present, after the synthesis, cementing characteristics in the materials, this process is known as geopolymerization or alkaline activation (Arias *et al.* 2018, Emanuel *et al.* 2019). The combined action of chemical stabilization of minerals such as those found in silica-rich clay, by adding $Ca(OH)_2$ and NaOH, and mechanical stabilization using Proctor, allows achieving good final performance of this residue.

Recently some authors have used the finite element method (FEM) with computational techniques to assist the design and thermal behavior of building elements and systems, taking into account weather and conditions for a particular region (Svoboda 2011, Liz *et al.* 2019). In this paper, an SQS block was simulated through FEM, to observe its thermal performance regarding other common building materials, according to Medellin city weather conditions.

2 METHODOLOGY

2.1 Stabilization Experimental Design

Previous studies (Restrepo and Zapata 2020) with SQS allowed to obtain a mix of 7% $Ca(OH)_2$ and 8% Na(OH) 10 M that gave, as a result, an improvement of the mechanical performance of the SQS. X-Ray Fluorescence for the chemical composition of the employed materials is presented in Table 1.

Table 1. XRF Materials Composition (% wt).

Material	SiO_2	Al_2O_3	CaO	Fe_2O_3	MgO	Presentation
Stabilized Quarry Sludge (SQS)	52.31	16.37	3.24	9.78	2.19	Particle minor to 75 μm
Commercial $Ca(OH)_2$	4.6	0.6	91.3	0.3	1.8	
Commercial Na(OH)	-	-	-	-	-	Flakes (98 % of Purity)

Cylindrical test specimens were fabricated by mixing Quarry Sludge (QS) with water and stabilizers in the previously mentioned quantities. The optimum water content was computed through a modified proctor compaction test (ASTM D1557), achieving the maximum compaction density. With these conditions, SQS test specimens were compacted and cured for 7 days at 40°C in the furnace with a relative humidity of 95%. With the time done, the specimens were dried and tested according to the unconfined compression strength standard (ASTM D2166) with an HM 3000 compression Humboldt machine in a load cell of 20 kN. Specimens achieved a UCS up to 8MPa, this allowed the classification of this material as a Type 5 structural block (UNE EN 41410). Subsequently, a mineralogical XRD analysis of the SQS was performed to assess the possibilities of cementing phase formation.

2.2 Computational Simulation

A computer simulation using FEM was performed for analysis of heat transfer of the SQS building element and compared with other typical construction materials Table 2. Besides the local weather (Temperature and humidity) data, from, Early Alert System of Aburra Valley, in Spanish "*Sistema de Alerta Temprana del Valle de Aburrá* (*SIATA*)", was used to analyze the thermal load of a wall guaranteeing a comfort temperature (25°C), during the warmest month, this to achieve a quick methodology for the performance of sustainable and low-cost materials avoiding the use of fans or AC devices. In Figure 1(A-E) the walls are shown, for different materials to simulate in this study, see Table 2. The walls are composed of blocks or bricks with one or two cavities.

Table 2. Thermal properties of wall systems material.

Material	K (W/m*K)	Cp (J/kg*K)	ρ (kg/m³)	Reference
(A) Fiber Cement board (FC)	0.230	1250	1135	
(B) Clay	0.720	921	1800	Yunus 2013.
(C) Concrete	0.885	920	2300	
(D) Oriented strand board	0.450	1360	550	Suarez 2018.
(E), (F) SQS	0.846	900	2000	

Based on the work of (Borbon et. al 2009), for blocks with hollows, a resistance method was used to compare with non-linear-FEM. In Figure 1(F), for each domain, we have a system of equations, based on the number of the solid regions, partitions, between the hollows of the masonry element. So we have *i* equations, where *i=1,2,..* . In the case of concrete blocks, we have one partition. The heat transfer on the air in the cavity was excluded from the analysis, instead, the convection coefficient from the correlation for parallel plates (vertical or horizontal) was used (Yunus 2013). A partial differential equation (PDE) Eq. (1) and boundary conditions (BC) Eq. (2) and Eq. (3) are applied, also, a Crank-Nicolson scheme was performed to simulate the effects of external weather variations in time. The BC order depends on the positions of the block. *Ti(x)* is the temperature of the domain in the face *i* of the cavity, *(i=1,2*). *To* is the external temperatures outside the masonry element.

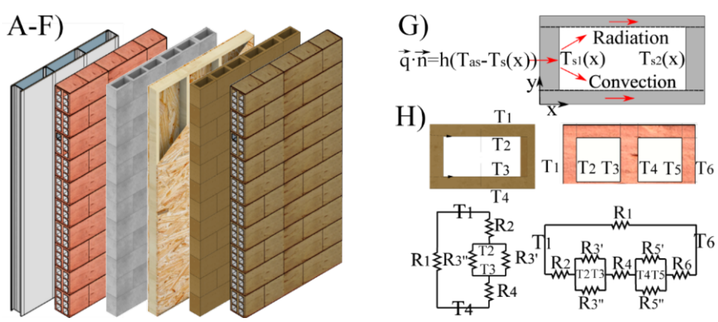

Figure 1. (A-F) Building systems walls. (G) scheme of heat transfer on the block-hollow. (H) diagrams of resistance for elements with one hollow and two hollows.

$$\frac{\partial T_i}{\partial t} - \frac{k}{Cp\rho}\frac{\partial T_i(x)}{\partial x^2} = 0 \tag{1}$$

$$q_i\,|_{(xi=Li)} = h(T)(T_i(x_i) - T_t) + \alpha\varepsilon(T_i(x_i)^4 - T_t^4) \tag{2}$$

$$T_i(x_i) = T_o \tag{3}$$

The convective coefficient was obtained from the naturally enclosed convection correlations. Eq. (4). Where, *ka* is the heat conduction coefficient of air, *Lc* is the cavity length. *Tt* is the temperature of the face in front of partition *i*. Every *i* equation has its own *Tt*. Due to the number of nonlinear terms in the equations, *Tt* is taken like a guess term for an iteration method.

$$h(T) = \frac{k_a}{L_c}N_u;\; N_u = 0.065 R_{aL}^{1/3};\; R_{aL} = P_r G_r \tag{4}$$

Two different BC were implemented on the external face. First, a Dirichlet B.C. to get the accuracy of the method, by comparison with a thermal-*resistance* scheme (Figure 1(G)), which considers the effects of radiation and convection in the hollow, both at a steady-state. After that, a Robin (convection) B.C, using the highest sol-air temperature from SIATA. The convective term for this condition was computed through a standard (NCH 853 2007). Then a simple analysis of heat flux for different materials was performed to select the most suitable compared with the SQS block.

3 RESULTS AND DISCUSSION

3.1 Experimental

The unconfined compressive strength for SQS material is favored by the concentration of Na(OH) this is due to the ability to form zeolite-type compounds (Arias *et al.* 2018), which can accompany the presence of cementing phases of the geopolymer type (See Figure 2).

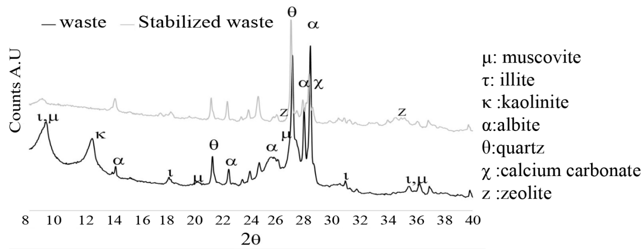

Figure 2. SQS XRD.

On the other hand, the use of $Ca(OH)_2$ reduces the plasticity of the SQS in contact with water and improves the compactness conditions, which makes it possible to obtain a higher density and durable matrix in the block manufacturing process.

3.2 Simulation

In Figure 3 FEM is compared with the resistance method, for a common concrete block and a clay brick, also a simple error analysis for temperatures and heat flux is presented. In Figure 3(A), the accuracy of the method depends significantly on the number of the hollows and the hollow length, which is a sensitive parameter to handle, due to the error analysis. The relation between *L* and *Lc* must be *Lc=6L* for good accuracy. This mismatch between FEM and the resistance could be explained by the number of non-linear terms. Besides, the method captures the same tendency of the temperature profile for the external partitions. For a single cavity Figure 3(B), the method has good accuracy and the effect of hollow length is insignificant.

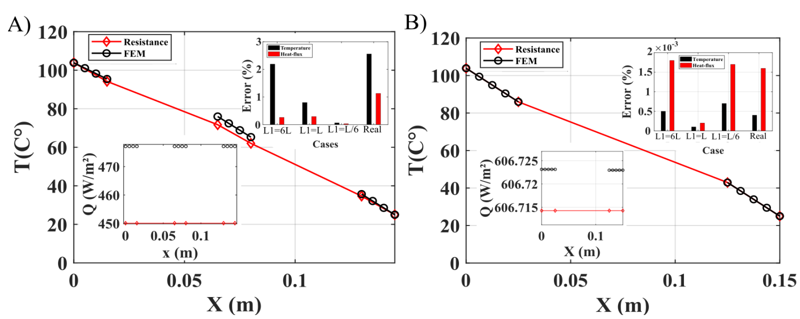

Figure 3. (A) Clay brick error analysis. (B) Concrete block error analysis.

In Figure 4(A), the same methodology was implemented in the thermal behavior analysis of the wall-building systems presented before (Table 2). Based on the overall heat flux calculated over each material, the Fiber Cement (FC) wall system presents the best behavior. It is observed that block systems (Concrete and sludge) increase the heat values by around 225%, despite that, the sludge block achieves better thermal performance, decreasing the flux 3.37% concerning the same system but with concrete material. Sludge brick and OSB, showed a 3.0 % difference in its thermal behavior, according to this, can be affirmed that the simplest stabilized sludge way, can represent a thermal comfort, in Medellin city conditions, the same as OSB.

In Figure 4(B-C), It is verified that the nonlinear-FEM approach can solve transient equations for a Dirichlet B.C. See Figure 4(B), and a Robin boundary condition, see Figure 4(C) for a single-hollow block. Once the applied model in a non-steady-state was checked, the comparison between the SQS block and FC wall was done.

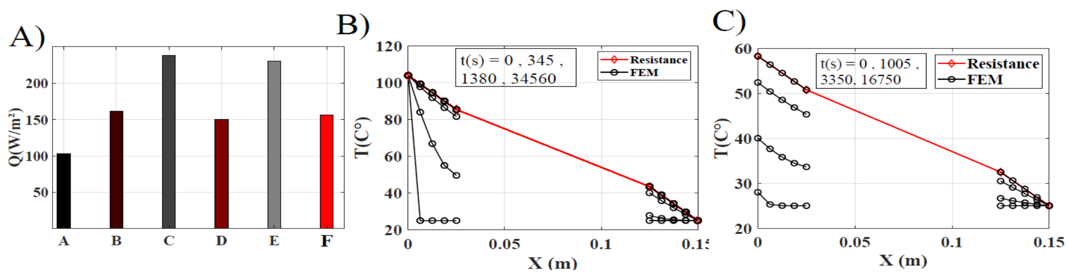

Figure 4. (A)Heat-flux comparison of different wall systems. (B) transient heat-transfer analysis for Sludge block fixing the external temperature as Dirichlet BC. (C) transient heat-transfer analysis for Sludge block applying a convection BC on the external face, *q=h(Tsl-Ts)*, where *Tsl*=100°C.

In Figure 5 can be observed that the thermal behavior, temperature, and total heat flux, have the same tendencies as the sol-air temperature. It is clear that the FC system has a lower oscillation tendency concerning the external temperature conditions, and the difference between the internal faces temperature is the same. In the SQS block case, the two internal temperatures have a notable difference. Furthermore, maximum hollow temperatures were analyzed and there was identified the time in which they took place, it was also calculated the average mismatch ($_2$) along the month, obtaining a value of 145.16 seconds for the FC system, whilst the SQS block showed a mismatch of 305.81 seconds, representing 110% difference.

For the FC wall, it obtained an average heat-flux of 23.1 W/m² whilst for the SQS block the average heat-flux was 35.6 W/m², which represents an increase in the thermal load of 54.1% by transmission in the building (λ). Thus, a correlation is found between the heat mismatch and the thermal load $2\lambda \simeq \tau_2$.

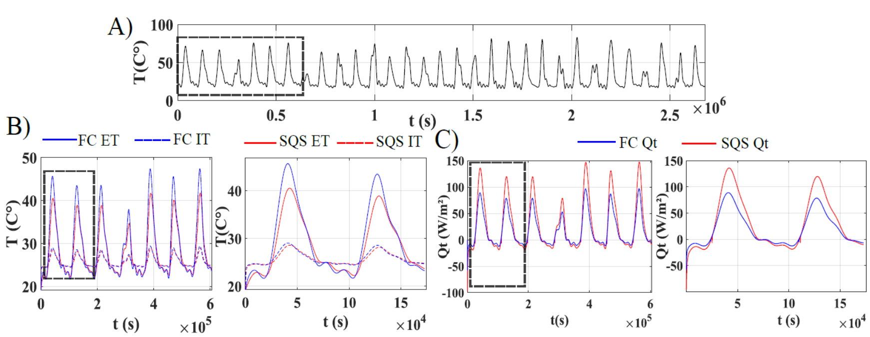

Figure 5. A) temperature sol-air taken from the SIATA data set of May (the warmest temperatures). B) Hollow internal faces temperatures for a week and two days for FC and SQS. (C) Total heat flux for a week and two days for FC and SQS.

4 CONCLUSIONS

It is possible to stabilize the residual sludge increasing the load-bearing capacity by 688%. Thus, reach the production of a block that accomplishes the UNE-41410 standard for structural (type 5) and non-structural blocks (type 3).

- A numerical model is developed suiting good to the theoretical solution, this allows an assessment of the heat transfer in building systems with one hollow between the wall faces, taking into account the following phenomena, conduction within the faces, exterior convection in-hollow radiation and in-hollow convection.
- The developed model for a two-hollow system does not deliver good results when the assessed area is considerably small, due to the highly non-linearity of the equations that describe the convection and radiation phenomena
- The models allow transient analysis, obtaining more suitable results according to reality, in contrast to the theoretical solution which does not offer this type of analysis.
- According to the numerical simulation, the SQS blocks presented a thermal performance equivalent to the OSB system, this allows its proposal as a building material, representing an innovation in the way of using industrial waste near to the source that generates it.
- For Medellin's city climate conditions, it is presented a heat transfer mismatch-thermal load correlation for the building systems.

References

Borbón, A. C., Cabanilles, R., and Pérez, J., *Modelación y Simulación de la Transferencia de Calor en Muros de Bloque de Concreto Hueco,* Información Tecnológica, 21(3), 27–38, 2009.

Emmanuel, E., Paris, M., and Deneele, D., *Insights on the Clay Reactivity in Alkaline Media: Beyond Filler Role for Kaolin,* Appl. Clay Sci., 181, June, 2019.

Hoyos, A., Arias, Y., and Tobón, J. I., *Evaluation of Cements Obtained By Alkali-Activated Coal Ash with NaOH Cured at Low Temperatures,* 68(332), 1–11, 2018.

Li, Z., Qiao, Z., and Tang, T., *Numerical Solution of Differential Equations: Introduction to Finite Difference and Finite Element Methods,* Cambridge University Press, 2017.

Official Chilean Standard Act of 2007, Standard. Thermal conditioning - Thermal envelope of buildings-Thermal resistance and transmittance calculation, NCh 853, 2007.

Restrepo-Ramirez, A. F., Zapata-Perez, N., Arias, Y., and Ochoa, J., *Residual Quarry Sludge Stabilization to Prefabricate Sustainable Building Elements* (Poster presentation), TMS 2020 149th Annual Meeting & Exhibition, San Diego, CA, United States, 2020

Suarez-Dominguez, E. J., *Resistencia Mecánica y Conductividad Térmica de Suelo Cemento Plástico con Adición de Fibra Vegetal*, Siacto, October, 2018.

Svoboda, Z., and Kubr, M., *Numerical Simulation of Heat Transfer Through Hollow Bricks in the Vertical Direction,* Journal of Building Physics, 34, 325-350, 2011.

Yunus, A. C., *Heat and Mass Transfer Fundamentals and Applications*, Journal of Chemical Information and Modeling, 2013.