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MECHANICAL ANALYSIS OF A SUSTAINABLE BUILDING PREFABRICATED ELEMENT BASED ON A STABILIZED RESIDUAL QUARRY SLUDGE

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A masonry prefabricated element will be produced from the process of reusing a sludge generated by the Colombian mining industry, especially the sandstone quarries, that become pollution agents ending up in the hydric sources, impacting negatively the environment. This waste was previously stabilized with the addition of $Ca(OH)_2$ and Na(OH), the optimal mixing specifications were obtained using a response surface model accomplishing low quantities of stabilizers and the use of the waste as the main component, achieving improvements in load-bearing capacity (8 MPa) and the durability according to its dimensional stability, upgrading the traditional techniques. In this work, computational simulations are performed to understand some mechanical responses in stabilized-sludge masonry elements with different geometries and to compare the simulation results with common materials in the literature. Simulation outcomes showed that hollow-block geometry saves up a considerable amount of material and improves stress distribution compared with a solid block. Also, the mechanical simulation of the stabilized-sludge elastic zone achieved a better performance than a compressed earth block, which is a similar material used in construction. This way, the design of more sustainable elements through an innovative methodology based on statistics, mathematical and computational models, saving materials, time, and energy is sought, generating an economic and environmental impact.

Keywords: Mining waste, Alkali activated, Computational simulation, Mechanical sustainable block, Stabilization.

1 INTRODUCTION

Quarry sludge (QS) is originated from a differential sandstone washing site in rocky materials quarries. This waste is found as a paste or hydro-mix, generated during the treatment process material. It contains a high solid/liquid ratio, and a grain size classified between silt and clay (2.0-0.0625 mm). 30% of QS production is used in the ceramics industry (bricks and tile production), and 70% remaining is thrown away in garbage dumps. This wrong disposal allows its ending into the hydric sources directly affecting the environment. As a fact, in 2015 Colombian rocky materials exploitation used in the construction industry stood at 33,033,666 m³, being 6% the sludge generation equivalent to 1,982,019 m³, without taking into account illegal processes. Also, monthly a single quarry can reach a production of 16.000 tons.

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 show, after the synthesis, cementing characteristics in the materials. This process is known as geopolymerization or alkaline activation (Hoyos *et al.* 2018, Emmanuel *et al.* 2019, Balaguera *et al.* 2019). QS used in this work presents high concentrations of SiO_2 and Al_2O_3, which can be used to carry out a cementing process with Na(OH). However, these mixes are not a guarantee of the formation of cementitious phases. In road construction, knowledge of the maximum densities and optimal soil moisture is essential to achieve mechanical stabilization.

The combined action of chemical stabilization of minerals such as those found in clay-rich in silica, by adding $Ca(OH)_2$ and Na(OH), and mechanical stabilization using Proctor, allows achieving good final performance of this residue. It was necessary to propose an experimental design with high confidence to determine the best stabilization conditions to make use of the residue. Finite Element Method (FEM) simulations were carried out seeking its validation with the experimental results. Thus, a further simulation was performed to get to know the probable elastic behavior of a masonry unit with specific commercial dimensions, using stabilized quarry sludge (SQS) as the main material. In this way could be understood the mechanical responses in the masonry element.

2 METHODOLOGY

2.1 Stabilization experimental design

Based on (Poinot *et al.* 2018 and Shubbar *et al.* 2019) stabilizers were chosen according to the waste nature and satisfactory results. Literature stabilized waste achieved improved behaviors in unconfined compressive strength (UCS), absorption, thermal conductivity, i.a., thus, a reference dosage for mixes is defined for applying statistics to cover more possible stabilizers-waste proportions. 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)

After defining materials, a central composite design of response surface was used with a value of α =1.414 and 2 replications, with a total of 26 experimental runs. The levels of the factors used were 5% and 9% of Ca $(OH)_2$ by weight (w/w %), 4 and 12 molar of Na(OH). In Figure 1(A) is presented as a list, the different mixes of QS and stabilizers. Each mix is identified with a specific color and a number. C goes as control meaning that it is the raw QS with no addition. Moreover, the experimental design model used can be observed in Figure 1(B).

The experimental design is supplied with the information obtained from several tests, e.g., modified Proctor test where optimum compaction humidity and maximum dry density were measured. Besides, cylindrical test specimens of 10 cm high by 5 cm in diameter were made.

The main response variable measurement for each mix was the load-bearing capacity, which is the unconfined compressive strength (UCS) of the specimens at 7 days of curing at 40 °C with 95% humidity. With all the results, several response surface models were determined. Finally, the data was analyzed through the experimental design and its statistics values, establishing an optimum mix, thus a building prefabricated element will be produced for further research.

A)

Admixture	$Ca(OH)_2$ (w/w%)	Na(OH) w/w% (Molar)
C	0%	0% (0)
2	7%	2.34% (10.34)
3	7%	8% (9.36)
4	7%	13.66% (10.19)
5	9%	12% (12.39)
6	5%	4% (8.41)
7	4.17%	8% (13.44)
8	9.82%	8% (12.26)
9	9%	4% (13)
10	5%	12% (7.28)

B)

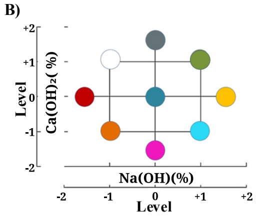

Figure 1. (A) Experimental matrix. (B) Central composite experimental design.

2.2 Computational simulation

FEM-based software (Abaqus) was used for the computational results, elastic linear behavior was simulated using the experimental information, Young's modulus. Besides, the Poisson ratio was taken from the literature (Ameri *et al.* 2009). Then computational results were validated, comparing the strain-stress curve with experimental ones. Also, a simple sensitivity analysis was applied to the mesh used. Finally, two different geometries of the SQS block were simulated to analyze the maximum strain distribution in both cases.

3 RESULTS AND DISCUSSION

A curvature effect in the UCS response surface is observed for $Ca(OH)_2$. See Figure 2(A). This is associated with an optimal value in the quantity to achieve the best compaction of the specimens. On the other hand, the increase in UCS is favored by greater concentrations 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 (3).

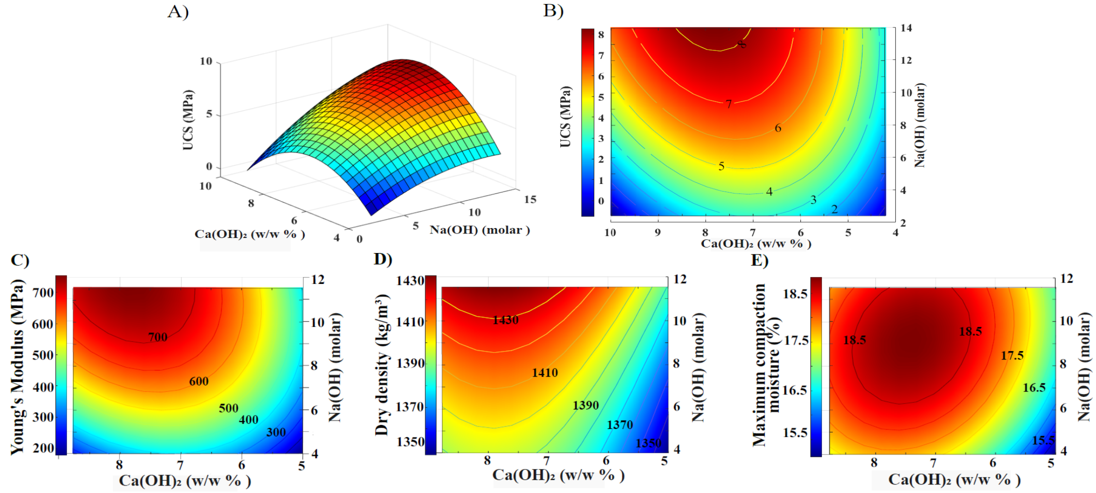

Figure 2. (A)UCS response surface. (B) UCS contour plot. (C) Young's modulus contour plot. (D) Dry density contour plot. (E) Maximum compaction moisture contour plot.

For a confidence level of 95%, it could be ensured that the regression model of the response surface presents an adjustment of 86%. In figure 2(C), Young's modulus has the highest performance with the highest content of Na (OH), resulting in greater strength. Likewise, in Figure 2(E), the use of $Ca(OH)_2$ reduces the plasticity of the SQS in contact with water and improves the compactness conditions. That makes it possible to obtain a higher density, see Figure 2(D), and a durable matrix in the block manufacturing process.

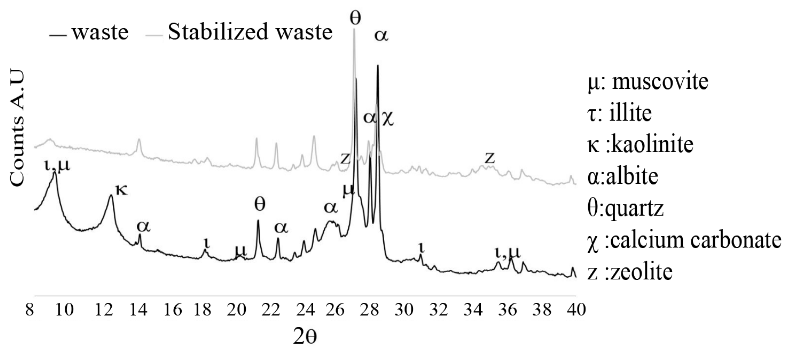

Figure 3. X-ray diffraction of SQS and QS.

In Figure 4(A) stress-strain curve is presented. It is observed that the optimum mix (#3), from the experimental design, is better than the control mix, raw sludge. Also, optimum mix slope is similar to Compressed Earth Block (CEB) cylinder, which was simulated using the elastic behavior (Cañola *et al.*2018) with FEM. Nevertheless, conventional CEB, with no stabilization, achieves a compressive strength of 3.4 MPa. For application of this stabilized material, UNE 41410 (2008) standard was used (Figure 5). It is observed that strengths of the control mix and the stabilized mix are acquired and the use of the material as a compacted soil block is determined, according to its category by compressive strength in MPa. Also, it can be seen that the optimum SQS mix can achieve up to 7.89 MPa, thus finding that SQS would have a better performance than conventional CEB.

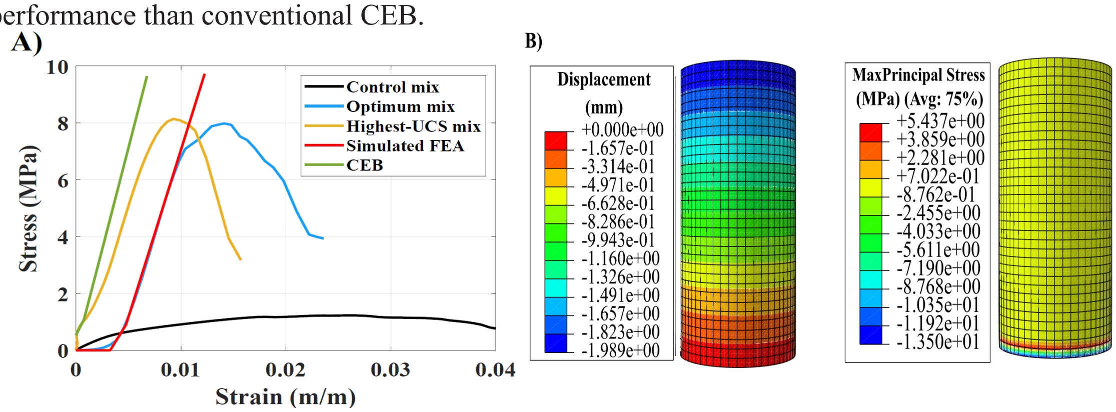

Figure 4. (A) Stress-strain curves. (B) Simulation of displacements and stress distributions for the optimum mix cylinder.

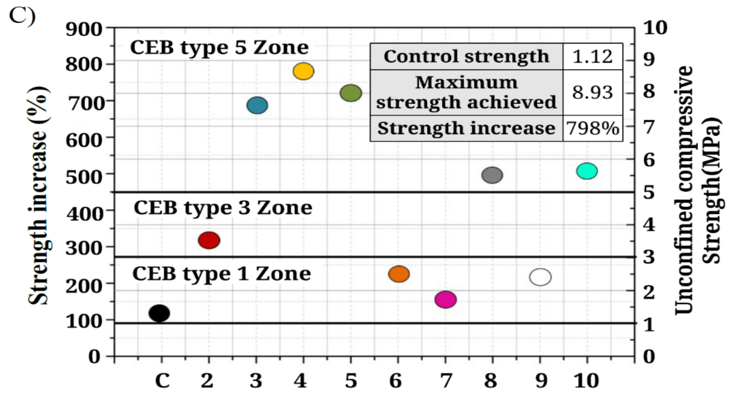

Figure 5. UNE 41410 (2008) mixes classification.

For the highest-UCS mix, (#4) from the experimental design, can be seen that its compressive strength result is due to a higher Na(OH) addition (30% more than mix #3). Even though the difference is almost one magnitude order as is shown in figure 4(C). In figure 4(B) stress distribution is accumulated on the bottom of the cylinder and there is a higher stress gradient.

In Figure 6, the behavior of an optimum mix SQS block (Case 3) was simulated. A sensibility analysis was performed for 4,906; 9,548; 12,527 nodes. The most optimum mesh size (less computational cost) was for 9,548 nodes. The stress distribution is accumulated on the boundaries of the block, and the presence of the hollow tends to minimize stress.

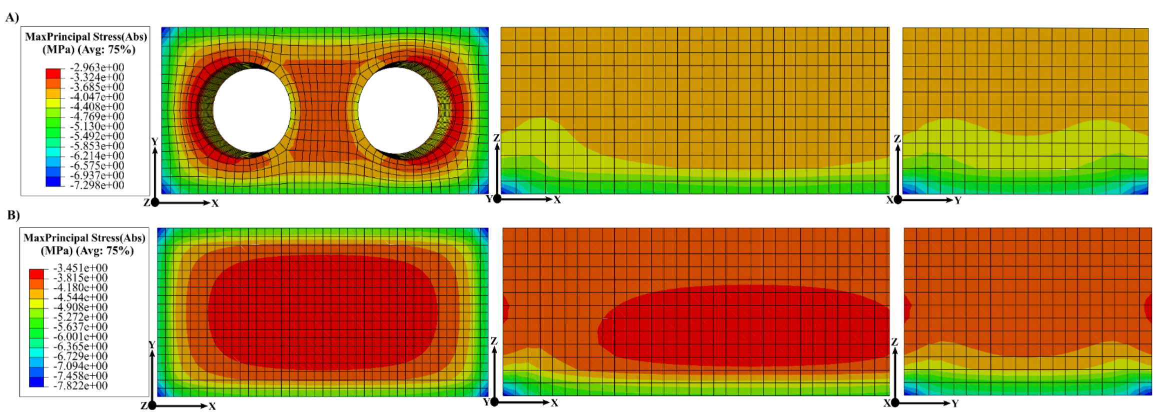

Figure 6. SQS linear response simulation. (A)Hollow block. (B) Solid block.

For a 4 MPa pressure simulation, the solid block showed stress concentrations around 7.822 MPa, more than the hollow block which has a stress around 7.298 MPa. The difference between them is 7% and the mass difference is 27 %. On the other hand, more simulations were performed and the results showed that if the solid block has a maximum compression strength in the elastic zone around 8 MPa it needs a material strength of 15.7 MPa, meanwhile a hollow block needs 14.6 MPa.

4 CONCLUSIONS

QS stabilization can be done, doing optimization processes with the response surface model obtained since the R^2 predicted is 86%. Since a load-bearing capacity improvement (688%) is achieved, the production of a block that accomplishes UNE 41410 (2008) standard for structural (type 5) and non-structural blocks (type 3) can be done.

The increase in the load-bearing capacity is due to Na(OH), followed by the curvature effect of $Ca(OH)_2$, which is presented in the UCS response surface.

Through the experimental methodology, mechanical properties of SQS cylinder were reported, meanwhile, FEM-based simulation was performed to understand the shear distribution and the maximum load material could bear.

Hollow geometry aids stress distribution improvement. Simulation results showed that an SQS solid block achieves more strength than a conventional CEB. Block geometry variations allow optimization in stress accumulation, reaching a higher strength. With these simulations, SQS minimum strength can be obtained for desired masonry unit behavior.

A 4 MPa pressure generates around 8 MPa maximum stress on SQS hollow and solid blocks, according to computational simulations, that is why the load is borne. Nevertheless, experimental block testing must be done to validate these results.

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