Use of papermaking sludge in the manufacture of bricks for the construction of non-structural walls

Uso del lodo Papel en la elaboración de mampuestos empleados en la construcción de muros no-estructurales

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ABSTRACT

The high levels of waste cellulose mud in paper production represent a severe environmental problem regarding its final disposal as a waste by-product. The accumulation of paper sludge and its possible recycling should be focused on its reuse in primary materials or those of continuous use that mitigate its environmental impact. This research was developed to characterize a clay material used in civilian construction with Eco-Efficient properties (hollow ceramic bricks), incorporating waste from paper factories (paper sludge or cellulose sludge) without affecting its mechanical response in comparison with traditional materials, but with the use and advantages of the utilization of residual materials. For this purpose, a physical-chemical characterization of the paper sludge was carried out, accompanied by a physical-mechanical characterization for the Non-structural block obtained with the inclusion of the sludge, in accord with dosages of 0%, 11.1%, 12.5%, 14.3% 16.7% and 20%. As a result, the organic and inorganic byproducts present in the paper waste byproducts were obtained, and the hollow ceramic bricks showed an increase in their mechanical compression capacity under considerable variations in coloration and size.

Keywords: Paper sludge, waste byproducts, eco-efficient, non-structural brick, dosage, physical-chemical, mechanical, coloration.

RESUMEN

Los elevados niveles de residuos en la producción papelera representan un severo problema ambiental en cuanto a su disposición final como subproducto de desecho. La acumulación de residuos celulósicos y su posible reciclaje debe enfocarse a su reutilización en materiales primarios o de uso continuo que mitiguen su impacto ambiental. Esta investigación fue desarrollada para caracterizar un material arcilloso utilizado en la construcción civil con propiedades Eco-Eficientes (ladrillos cerámicos huecos), incorporando residuos de fábricas de papel (lodos de papel o lodos de celulosa) sin afectar su respuesta mecánica en comparación con los materiales tradicionales, pero con el aprovechamiento y ventajas de la utilización de materiales residuales. Para ello, se realizó una caracterización físico-química de los lodos de papel, acompañada de una caracterización físico-mecánica para el Bloque No Estructural obtenido con la inclusión de los lodos, de acuerdo con dosificaciones del 0%, 11,1%, 12,5%, 14,3%

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16,7% y 20%. En consecuencia, se obtuvieron los subproductos orgánicos e inorgánicos presentes en los subproductos de residuos de papel, y los ladrillos cerámicos huecos mostraron un incremento en su capacidad de compresión mecánica bajo variaciones considerables de coloración y tamaño.

***Palabras clave**: Lodos de papel, subproductos residuales, eco-eficiente, ladrillo no estructural, dosificación, físico-química, mecánica, coloración.*

INTRODUCTION

Recycled paper sludge (RPS) is a waste residue originating from paper recycling, more specifically, from treating the liquid effluents generated in that process [1]. The number of products and their different derivatives make it one of the commodities with the highest worldwide production, resulting in one of the worst forms of waste handling. The statistical analysis has established that Europe has a production of 11 million tons per year, Korea 21 million tons, and Japan 5.1 million tons [2], [3]. All this corresponds to the fact that the paper is massively produced, and its waste causes environmental damage. Currently, to regulate the production, handling, and disposal of paper waste, there are applicable norms at a global and national level, such as Resolution 2309 of 1986 [4], Law 430 of 1998 [5], and CONPES 2705 of 1994 [6], which establish the criteria for waste identification, compliance and safety plans for the proper disposal of solid waste.

According to a report by the Environmental Paper Network, paper consumption has reached unsustainable levels and is increasing steadily globally. It recently exceeded 400 million tons per year globally [7]. In Colombia, the problem of waste is increasing, and it is necessary to look for alternatives to the use of solid waste produced in paper manufacturing processes to avoid the large amount of waste that ends up in landfills. A survey showed that 68% of Colombians prefer the printing of paper documents over their use in the form of digital documents, 87% prefer legal documents also in physical form, just as 75% of the population prefer reading books on paper [8], a total consumption of 1,650,537 tons of paper, maintaining the growth trend in recent years, with an increase of 3% [9]. Solid waste production is approximately 30,000 tons of garbage per day, of which approximately 92% are disposed of mainly in sanitary landfills, while the reuse of waste generated at the national level is between 5% and 7% [9]. All of the above negatively impacts the environment. Using these waste residues in construction can be a significant advance towards optimizing and handling of waste emitted in the environment, generating a greater capacity in sanitary landfills and reducing the emission of waste residues [10].

In the search for new paper sludge recycling (RPS) alternatives, its use has been proposed under the process of saccharification of waste paper pretreated with hydrogen peroxide in manufacturing polyhydroxyalkanoate (PHA) -based bioplastics. This product has been increasingly used in the last decades as a substitute for petrochemical products based on plastics.The use of paper waste as a source of carbon for the production of polyhydroxy butyrate (PHB), this being one of the most studied members of the family of polyhydroxyalkanoates (PHA), is a form of waste handling that does not affect the environment and provides value to paper waste in the modern world [11].

In addition, research was conducted on the mechanical and durability of recycled aggregates concrete (RAC) containing 100% coarse recycled concrete aggregates (RCA) and industrial byproducts such as mud ash (PSA), and fly ash (FA), silica fume (SF) and metakaolin (MK) in different proportions (5%, 10%, 15%). In this study, two methods were used: replacement and addition. The addition of industrial by-products has been revealed as a promising alternative to Portland cement augmentation in RAC to improve its quality. The results showed that the strength and durability of the mineral additives containing RAC in the addition method were more significant than the cement increment or the replacing method. As for the paper mud ashes (PSA), the mechanical properties of (RAC) improved considerably at an early age and substantially improved the resistance of RAC to acid and sulfate attacks within 90 days [11].

Studies on the benefits of paper sludge have led to the creation of a hydrophobic powder as a water-repellent additive used in coating surfaces for concrete. The powder was produced from paper mud ashes (PSA), improving work, strength, and transport properties, including sorptivity, water absorption, diffusivity, permeability, and electrical conductivity. It was found that replacing Portland cement with 12% of PSA reduces water absorption, sorptivity, and conductivity by 84%, 86% and 85%, respectively, without major detriments, effects associated with hydration, strength, and density. When it is used as a surface coating, hydrophobic PSA reduces both absorption and sorptivity by 85-99%, depending on the adhesive used. Results translate into attaining water-repellent and self-cleaning surfaces [12].

This work sought to reduce the environmental impact produced by waste (RPS), through its inclusion in the field of engineering, more precisely in the construction sector. It focused on the preparation of *hollow ceramic bricks*. Starting with the physical-chemical characterization of the paper sludge, establishing the contents, and adding slug paper in the mixture composed initially of clay (granson) and sand. Finally, measure the physical-mechanical behavior of the experimental test brick.

MATERIAL AND METHOD

The materials used refer to the material of *hollow ceramic bricks* and the experimental additive to be added called sludge paper. Below, a brief description of each one will be made, in addition to the physical, chemical, and mechanical characterization tests, with the normative employed.

Hollow ceramic brick material

For the elaboration of *hollow ceramic bricks*, it is necessary to mix two natural materials, such as clay (granson) and sand, that, under a cooking process, give rise to non-structural masonry [13]. The soil used for the collection of materials is a sample of the materials used by the "San Joaquín" brick factory located in the department of Cundinamarca, municipality of Colombia, at Km 12 on the highway from Zipaquirá to Ubaté.

This sector in Colombia is known for its commercial performance in molding clay to cook it and produce bricks, roofing, and tiles since the soil is widely used for the ceramic industry.

The clay and the sand come from excavating the different rocky massifs in the sector. This extraction has been carried out since 1960 in an artisanal manner and industrialized way since 2003. Clay and sand have been used to create different ceramic materials for civilian construction, such as *hollow ceramic bricks*; Massive blocks for structural and non-structural walls. They are commercially known as vertical, horizontal, and solid drilling bricks. Their classification depends on the mechanical compression parameters and their use on-site [14], [15].

For our work, we used *hollow ceramic bricks* with dimensions 10 * 20 * 30 cm, which have horizontal perforation parallel to the face and sitting surface in non-structural masonry walls, used in dividing walls that do not provide resistance to the structural system [16]. The above is due to the uncertainty regarding the variation in its mechanical properties due to the addition of paper sludge.

Paper sludge material

There are four stages during the manufacturing process of paper:

- Reception and storage of recycled paper, depending on its quality.
- Preparation of the paste, which consists of several phases of purification to eliminate unwanted materials.
- Paper manufacturing, where the paste is transformed into a continuous sheet rolled into a large coil.
- Winding, rolling, and labeling.

During the manufacturing process, two main residues of the process are generated. One for rejection consists of materials that cannot be incorporated into the process of manufacturing paper associated with plastics, and another has a destination with an approximate percentage of 95%, consisting of cellulose and minerals, such as kaolin and limestone, known as paper sludge (RPS). Typically, this sludge is formed by mixed agglomerations of organic material called cellulose and inorganic material clay minerals and limestone of different shapes, sizes, and having a gray coloration [16], Figure 1.

RPS physical-chemical characterization

Within the physical characterization of the paper sludge, tests were developed to determine density, electrical conductivity, humidity ratio, cationic

Figure 1. The appearance of the sludge paper prepared as an additive for the dosage of mixtures in hollow ceramic bricks.

exchange capacity, and organic carbon oxide content, among others, according to NTC-5167 [17]-[19]. Table 1 shows the total composition of solids and the percentages of organic and inorganic materials.

Hollow ceramic bricks dosage

The variation of the compression mechanical properties of the hollow ceramic bricks, as a function of the addition of RPS, was measured by taking into account the brick-making process at the "San Joaquín" brick factory, where the manufacturing process is carried out with shovels or proportions depending on the ratio of sand and clay. The dosage D-0 corresponds to the original mixture by the brick factory, while the dosages of D-1 to D-5 incorporate the paper sludge in percentages of 11.1% up to 20%. In Table 2, the Design of dosages of *hollow ceramic bricks* synthesizes the above [20].

The dosage percentages used are due to the experimentation previously carried out for the development of this investigation, where it was observed that an increase in the paper sludge for the bricks would cause a significant reduction in their final dimensions, which is why they would not be accepted. For civil construction, similarly, a dosage below 10% did not show a change in the physical-mechanical properties of the bricks; for this reason, the dosage range between 11.1% and 20% was chosen.

Table 1. Organic and inorganic composition.

Parameters/study	Result	Units	Analytical method
Total Solids	**31.9**	**%**	
Ashes (inoranic material)	11.8	%	Gravimetric(NTC-5167)
Volatization Losses	21.1	%	Heating Muffle 750°
Organic material	88.2	%	Addition nitric acid

Table 2. Design of hollow ceramic bricks (10 * 20 * 30 cm).

Dosage	Un	Yellow sand	Clay (Granson)	Paper sludge	Total
D-0 (0%)	Rat	2	6	0	8
	%	25.0%	75.0%	0.0%	100.0%
D-1 (11.1%)	Rat	2	6	1	9
	%	25.0%	75.0%	12.5%	112.5%
D-2 (12.5%)	Rat	1	6	1	8
	%	12.5%	75.0%	12.5%	100.0%
D-3 (14.3%)	Rat	1	5	1	7
	%	12.5%	62.5%	12.5%	87.5%
D-4 (16.7%)	Rat	1	4	1	6
	%	12.5%	50.0%	12.5%	75.0%
D-5 (20.0%)	Rat	1	3	1	5
	%	12.5%	37.5%	12.5%	62.5%

Physical-mechanical characterization of bricks
These experimental bricks were tested according to the standard NTC-4205-2 [21], which establishes the requirements that bricks and ceramic bricks must meet as masonry units, fixing the geometric parameters with which the different types of units are determined, the physical ones such as the percentage of water absorption and mechanical ones such as those obtained in compression tests.

According to the Colombian technical standard, the percentage of water absorption for an average of 5 units must be below 17% under indoor use conditions and for outdoor use below 7-13.5%. Similarly, their compression strength should be higher than 3.0 MPa. Regarding their production, their size and weight should be at most 4% and 10%, respectively, from their original size and weight, and lastly, concerning marketing associated with color and texture. For the former, no variation greater than 40% should be observed regarding the original, nor should they present hollow or empty sounds. Table 3 shows the consolidation of the previous information from the Colombian Technical Standard and the production requirements established by the brick-making Company.

RESULTS AND DISCUSSION

The results will be broken down in terms of physical and mechanical properties based on the results listed above in Table 4 to Table 6 under the tests carried out by the NTC 42052 [21].

Table 4 shows the results associated with the physical properties of RPS. The high moisture content and retention reflect its ability to absorb water, even when removed from the plant. Conversely, the content of organic matter is associated with cellulose and hemicellulose, constituted by short fibers, used in the paper industry to give it characteristics of resistance [22], [23].

The chemical characterization did not show heavy metals such as mercury, lead, cadmium, and arsenic that could affect the mixture [20], and showed a MgO & CaO content lower than those studied by [20]; it is clear that this depends on each paper industry and its manufacturing process. Table 5 shows the chemical properties of paper sludge.

Absorption percentage
Once the water absorption test was performed on the masonry samples with the addition of paper

Table 3. Parameters of aptness.

Parameter/Aptitude	Variable	Observation.
Technical	Water Absorption	< 13.5%
	Comp. Resistance	>10Mpa
Production	Size	Does not vary more than 4% of its original size
	Weight	Does not vary more than 10% of its original size
Marketing	Color	Does not vary more than 40% of its original size
	Texture	Does not have empty sounds or gaps

Table 4. Physical properties of paper sludge, tests and measurable parameters.

Parameters / study	Result	Units	Analytical method
Total oxidable organic carbon	6.81	%	Walkley-Blacek (NTC-5167)
pH (saturation paste)	7.89		Potentiometer
Density	0.17		Gravimetric (NTC-5167)
Moisture retention	142.54	%	Crucible
Moisture	68.1	%	Gravimetric (NTC-5167)
Electric conductivity	1.15	dS/m	Conductimeter
Moisture retention	134	%	Gravimetric (NTC-5167)
Heat exchange capacity	3.54	(me/100g)	Volumetric (NTC-5167)

Table 5. Chemical properties of paper sludge, tests and measurable parameters.

Parameters/study	Result	Units	Analytic Method
Organic Nitrogen	0.19	%	Micro-Kjeldhal (NTC-5167)
Total Phosphorus (P205)	0.05	%	Colorimetric (NTC-5167)
Total Potasium (K20)	0.03	%	Atomic absorption (NTC-5167)
Total Calcium (CaO)	9.35	%	Atomic absortion (NTC-5167)
Total Magnesium (mgO)	0.13	%	Atomic absortion (NTC-5167)
Total Sulfur	389	p.p.m.	Turbidimetric (NTC-5167)
Total Iron	622	p.p.m.	Atomic absortion (NTC-5167)
Total Manganese	20	p.p.m.	Atomic absortion (NTC-5167)
Total Cupper	13	p.p.m.	Atomic absortion (NTC-5167)
Total Zinc	38	p.p.m.	Atomic absortion (NTC-5167)
Total Boron	3.3	p.p.m.	Colorimetric (NTC-5167)
Total Sodium	0.02	%	Flame emission (NTC-5167)

sludge, a proportional increase was observed between the addition of the content of the paper sludge and the percentage of absorption of the material, see Table 6. Associated with the high moisture retention percentage of the paper sludge referred to in Table 2. Physical properties of paper sludge, tests, and measurable parameters.

Figure 2 introduces the results in a scatter diagram with a linear equation that predicts the percentage of absorption based on the incorporation of paper sludge in ranges from 0% to 20%.

Resistance to compression

Similarly, for the compression strength test in the masonry samples under the addition of paper sludge, a proportional increase was observed between the addition of the paper sludge content and the resistance to compression of the material. Table 7 lists the results, and Figure 3 provides the equation of resistance to compression of the masonry

Table 6. Ratio - Addition paper sludge Vs. Water absorption.

Dosage	% of addition Paper Sludge	% of Water absorption
D-0	0.0%	6.4%
D-1	11.1%	8.2%
D-2	12.5%	10.5%
D-3	14.3%	12.1%
D-4	16.7%	13.9%
D-5	20.0%	16.7%

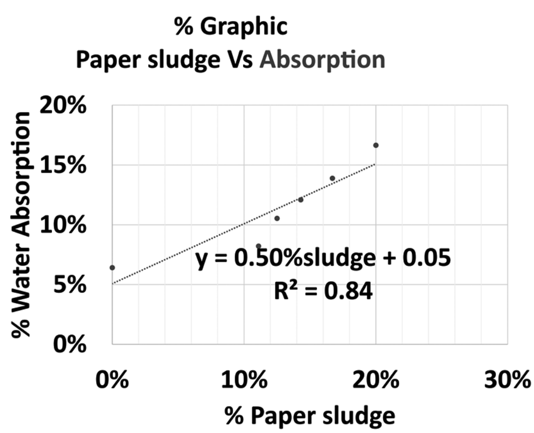

Figure 2. Graphical dispersion data paper sludge Vs % water absorption.

based on the incorporation of the paper sludge as a percentage of the mixture. This result is contrary to that set forth by [20], who experienced reductions in the resistance of their test samples by mixing more experimental additives such as fly ash and different types of quarry material, which increased the variables associated with experimentation and showed decreases of up to 50% and increases in some cases leading to high volatility in the research [24], [25].

In Table 8, The technical results of absorption and compression resistance and other additional factors related to the production characteristics (size, weight) and commercialization (color and texture), were consolidated, comparable to the aptness parameters referred to in Table 5. The results obtained from the

Table 7. Ratio addition paper sludge Vs. Resistance to compression.

Dosage	% of additio Paper Sludge	Compression Resistance (Mpa)	Compression Resistance (kg/cm2)
D-0	0.0%	6.3	63.9
D-1	11.1%	7.5	76.5
D-2	12.5%	6.6	67.5
D-3	14.3%	13.1	133.3
D-4	16.7%	13.9	141.6
D-5	20.0%	16.7	169.7

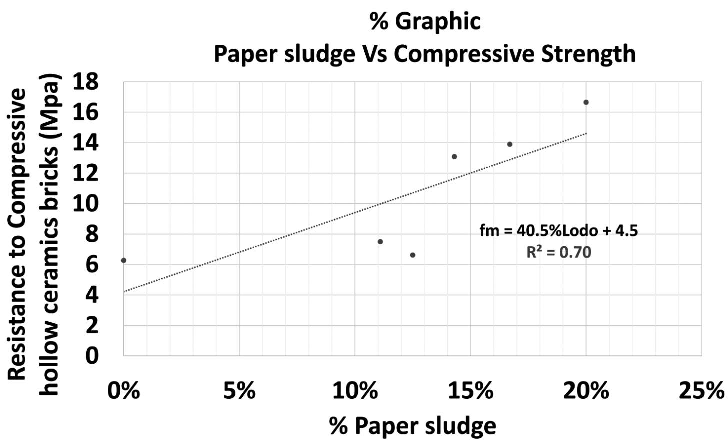

Figure 3. Data dispersion chart sludge Vs. Resistance to compression.

Table 8. Summary table of physical-mechanical characterization results.

		Dosage					
		D-0 (0%)	D-1 (11.1%)	D-2 (12.5%)	D-3 (14.3%)	D-4 (16.7%)	D-5 (20.0%)
Parámeters	Color	Salmon	Salmon without streaks (Figure 4)	Salmon red streaks (Figure 5)	Salmon white small streaks (Figure 6)	Dark salmon white streaks in more than 70 % (Figure 7)	Purple/blue black streaks (Figure 8)
	Size (cm)	9 x 20 x 30	9.1 x 20 x 29.6	9.1 x 20 x 29.6	8.9 x 19.1 x 29	8.9 x 19.1 x 29.4	8.9 x 19 x 28.6
	Texture	consistent sound	consistent sound	consistent sound	consistent sound	hollow sound	hollow sound
	Weight (gr)	4750	4695	5016	5068	5260	5325
	compressive strength (Mpa)		6.27	7.5	6.62	13.08	8.49
	Water Absorption (%)	6.42	8.22	10.54	12.09	13.89	16.65

experimental masonry and the aptness parameters referred to were compared. Similarly, in the images from 1 to 5, the photographs of the batches of masonry used in this project are observed with additions of paper sludge in percentages of 11.1% up to 20.0%, showing changes in volume, appearance, and consistency.

The most relevant technical parameter of resistance to compression indicates that the dosage D-5 with 20.0% of addition of sludge paper Figure 8, reached the maximum effort with 16.39Mpa. However, it does not meet the standards because of color, weight structure, or water absorption (Table 8).

Figure 4. Dosage of 11.1% (D-1) in hollow ceramic brick.

Figure 5. Dosage of 12.5% (D-2) in hollow ceramic brick.

The dosage D-4, with an addition of 16.7%, meets the technical parameter of resistance but does not meet the physical parameters of absorption and color.

Figure 6. Dosage of 14.3% (D-3) in hollow ceramic brick.

Figure 7. Dosage of 16.7% (D-4) in hollow ceramic brick.

Since, like the D-5 Dosage, high color variations with the presence of veins and a considerable reduction in size were experienced. Figure 7.

The dosage D-3 with 14.3% complies with the characteristics of resistance to compression,

Figure 8. Dosage of 20.0% (D-5) in hollow ceramic brick.

absorption, and weight, but in terms of size and color, more is needed to meet the standards of aptness. Figure 6.

CONCLUSIONS

This study resulted in three fundamental conclusions. The first is associated with the acceptance of the addition of paper sludge by the original bricks mixture without affecting the mechanical properties of the brick. Even dosage 5 reached a compressive strength of 14 Mpa, much higher than that established by the Colombian Technical Standard NTC 4205-2 [21].

The second is associated with the increase in the water absorption capacity of the masonry, linked to the hygroscopic characteristics existing in the papermaking sludge. It has a directly proportional relates the addition of paper sludge. However, a high increase in paper sludge could cause a reduction in non-structural ceramic bricks. Therefore, it is recommended in future research to evaluate this condition.

Third, it was concluded that the best option to comply with the requirements of the NTC 5167 [17] [18], associated with a percentage of absorption, size, weight, and compression resistance and the quality requirements of the manufacturer in terms of color and texture, the *hollow ceramic bricks* with dosages D-1 (11.1%) and D-2 (12.5%) of addition of paper sludge, Figure 4 and Figure 5. A range of possibilities opens regarding the final disposal of paper sludge, which generates a profound impact on the environment [2]; this mitigates the exploitation of resources for the elaboration of masonry by allowing for the addition of RPS and finally allows for new exploration regarding the possible use of paper sludge in other materials used in civilian works, such as structural masonry.

REFERENCES

[1] D. Gomes, L. Domingues, and M. Gama, “Valorizing recycled paper sludge by a bioethanol production process with cellulase recycling,” *Bioresour Technol*, 2016, doi: 10.1016/j.biortech.2016.06.004.

[2] M.C. Monte, E. Fuente, A. Blanco, and C. Negro, “Waste management from pulp and paper production in the European Union,” *Waste Management*, vol. 29, no. 1, pp. 293-308, Jan. 2009, doi: 10.1016/j.wasman.2008.02.002.

[3] A.S. Nair *et al.*, “Waste office paper: A potential feedstock for cellulase production by a novel strain Bacillus velezensis ASN1,” *Waste Management*, vol. 79, pp. 491-500, Sep. 2018, doi: 10.1016/j.wasman.2018.08.014.

[4] *Resolucion-2309-de-1986*, Ministerio de Salud, Colombia, 1986.

[5] Ley 430 de 1998, Ministerio de Minas, Accedido: Jun. 24, 2023. [En línea]. Disponible: https://www.suin-juriscol.gov.co/viewDocument.asp?ruta=Leyes/1832045

[6] *CONPES 2750 de 1994*, Ministerio de Ambiente, 1994.

[7] Environmental Paper Network, “The State of the Global Paper Industry-2018| Environmental Paper Network,” environmentalpaper.org (2018). [Online]. Available: https://environmentalpaper. org/stateoftheindustry2018/

[8] El Tiempo, “Investigación de TGI Net sobre medios impresos - Archivo Digital de Noticias de Colombia y el Mundo desde 1.990 - eltiempo.com,” eltiempo.com (2016). [En línea]. Disponible: https://www.eltiempo.com/archivo/documento/CMS-16564303 (Accedido: 24 Jun. 2023)

[9] Catalina Garnica Daza, "Alternativas de gestión de lodos papeleros en la Industria de papel Tisú y Kraft", Tesis de Grado, Facultad de Estudios Ambientales y Rurales, Universidad Javeriana, Bogotá, Colombia, 2013. [En línea]. Disponible: https://repository.javeriana.edu.co/handle/10554/12462

[10] A.D. Martínez-Amariz y G. Garrido-Silva, "Uso de la biomasa de residuos orgánicos para el diseño de una estación eléctrica", *Revista UIS Ingenierías*, vol. 18, no. 1, pp. 167-176, Jan. 2019, doi: 10.18273/revuin.v18n1-2019015.

[11] N.K. Bui, T. Satomi, and H. Takahashi, "Influence of industrial by-products and waste paper sludge ash on properties of recycled aggregate concrete," *Journal of Cleaner Production*, vol. 214, pp. 403-418, Mar. 2019, doi: 10.1016/j.jclepro.2018.12.325.

[12] H.S. Wong, R. Barakat, A. Alhilali, M. Saleh, and C.R. Cheeseman, "Hydrophobic concrete using waste paper sludge ash," *Cement and Concrete Research*, vol. 70, pp. 9-20, 2015, doi: 10.1016/j.cemconres.2015.01.005.

[13] F. Pacheco-Torgal, "Introduction to eco-efficient masonry bricks and blocks," in *Eco-efficient Masonry Bricks and Blocks: Design, Properties and Durability*, F. Pacheco-Torgal and P.B. Lourenço and J.A. Labrincha and S. Kumar and P. Chindaprasirt, Ed., Oxford, UK: Woodhead Publishing, 2015, pp. 1-10, doi: 10.1016/B978-1-78242-305-8.00001-2.

[14] D.M. Zárate, F. Cárdenas, E.F. Forero, and F.O. Peña, "Strength of Concrete through Ultrasonic Pulse Velocity and Uniaxial Compressive Strength," *International Journal of Technology*, vol. 13, no. 1, pp. 103-114, 2022, doi: 10.14716/ijtech.v13i1.4819.

[15] L. Pedreros, F. Cárdenas, N. Ramírez, and E. Forero, "NDT Non-Destructive Test for Quality Evaluation of Concrete specimens by Ultrasonic Pulse Velocity measurement," in *IOP Conference Series: Materials Science and Engineering*, vol. 844, no. 1, p. 012041, 2020. doi: 10.1088/1757-899X/844/1/012041.

[16] A.R.G. de Azevedo, J. Alexandre, L.S.P. Pessanha, R. da S.T. Manhães, J. de Brito, and M.T. Marvila, "Characterizing the paper industry sludge for environmentally-safe disposal," *Waste Management*, vol. 95, pp. 43-52, 2019, doi: 10.1016/j.wasman.2019.06.001.

[17] Productos para la industria agrícola productos orgánicos usados como abonos o fertilizantes y enmiendas o acondicionadores de suelo, NTC 5167, Instituto Colombiano de Normas Técnicas y Certificación (ICONTEC), p. 23, 2011. [En línea]. Disponible: https://es.scribd.com/document/227264366/Norma-Tecnica-Colombiana-5167#

[18] Productos para la industria agrícola productos orgánicos usados como abonos o fertilizantes y enmiendas o acondicionadores de suelo, NTC 5167, Instituto Colombiano de Normas Técnicas y Certificación (ICONTEC), pp. 21-22, 2011.

[19] Productos para la industria agrícola productos orgánicos usados como abonos o fertilizantes y enmiendas o acondicionadores de suelo, NTC 5167, Instituto Colombiano de Normas Técnicas y Certificación (ICONTEC), p. 11, 2011.

[20] P. Vashistha, V. Kumar, S.K. Singh, D. Dutt, G. Tomar, and P. Yadav, "Valorization of paper mill lime sludge via application in building construction materials: A review," *Construction and Building Materials*, vol. 211, pp. 371-382, 2019, doi: 10.1016/j.conbuildmat.2019.03.085.

[21] Unidades de mampostería de arcilla cocida. ladrillos y bloques cerámicos. parte 2: mampostería no estructural. NTC 4205-2, Instituto Colombiano de Normas Técnicas y Certificación (ICONTEC), 2009.

[22] Productos para la industria agrícola productos orgánicos usados como abonos o fertilizantes y enmiendas o acondicionadores de suelo, NTC 5167, Instituto Colombiano de Normas Técnicas y Certificación (ICONTEC), p. 13, 2011.

[23] Productos para la industria agrícola productos orgánicos usados como abonos o fertilizantes y enmiendas o acondicionadores de suelo, NTC 5167, Instituto Colombiano de Normas Técnicas y Certificación (ICONTEC), pp. 19-20, 2011.

[24] O. Kizinievic, V. Kizinievic, Y. Trambitski, and V. Voisniene, "Application of paper sludge and clay in manufacture of composite materials: Properties and biological susceptibility," *Journal of Building Engineering*, vol. 48, 2022, doi: 10.1016/j.jobe.2022.104003.

[25] A. Yaras, "Combined effects of paper mill sludge and carbonation sludge on characteristics of fired clay bricks," Construction and Building Materials, vol. 249, 2020, doi: 10.1016/j.conbuildmat.2020.118722.