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STUDIES OF GEOPOLYMER SAMPLES BY NON-DESTRUCTIVE TESTING

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ABSTRACT

Geopolymers are inorganic materials that have been studied since 1972 due to their advantages over Portland cement concrete, such as greater inertia, lower CO_2 *emissions, and greater chemical and fire resistance. The use of the ultrasonic velocity propagation technique, a non-destructive and widely used method for evaluating the quality of Portland cement concrete, has also been applied to geopolymers. However, the chemical composition and proportions of the materials used to produce geopolymers affect properties such as density, porosity, and absorption, which directly influence the propagation of ultrasonic waves. These factors indicate that the ultrasonic velocity propagation technique may not be entirely reliable for qualifying geopolymers, which is why more research on the subject is needed. Given this scenario, this study investigated how variations in the composition of geopolymer samples can impact the propagation speed of ultrasonic waves, considering an experimental design using response surfaces and taking into account the following variables: propagation speed of ultrasonic waves, compressive strength, absorption and specific mass. The results obtained demonstrated that the use of sodium silicate in geopolymer formulations to evaluate the propagation speed of ultrasonic waves, considering a significance level of 5%, was significant (p = 0.002), that is, less than* p_0.

KEYWORDS: *Geopolymer, Ultrasonic testing, Non-destructive testing.*

I. INTRODUCTION

Portland cement is consumed worldwide and plays a crucial role in the formulation of concrete and mortar. Its use is crucial for the workability of these materials in their fresh state, providing cohesion and strength after support, essential characteristics for the construction of complex and safe structures. However, its production involves industrial processes that cause significant environmental impacts. The main elements used in the manufacture of cement are clay and limestone, and their extraction results in soil degradation, destruction and collapse in quarries, a decrease in the amount of water in the beds from which the clay is extracted, and consequently, the aquatic fauna and flora.

One of the most important steps in the manufacture of cement is clinkerization, which consists of heating limestone and clay to approximately 1450 ºC to form clinker, a fundamental component of Portland cement [1, 2]. This process requires high energy consumption and results in the emission of around 900 kg of CO_2 for each ton of cement manufactured, contributing to approximately 5% of global CO_2 emissions [1]. In Brazil alone, in 2023, 62 million tons of Portland cement were produced according to the National Cement Industry Union – SNIC [3], which justifies investment in studies, research and new cement production processes or their replacement to reduce carbon dioxide emissions.

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In view of growing environmental concerns and global targets for reducing greenhouse gases, researchers and sustainability organizations, such as the World Business Council for Sustainable Development (WBCSD) and the Cement Sustainable Initiative (CSI), are investigating alternatives to Portland cement that reduce carbon emissions and mitigate environmental impact.

Geopolymers, which are inorganic materials manufactured from the activation of aluminosilicates with alkaline solutions [4], are one of these alternatives and stand out for their ability to be produced from a variety of raw materials, including industrial waste, such as fly ash and amphibolite, blast furnace slag and metakaolin [5,6]. These precursors, when combined with a solution of sodium hydroxide or potassium hydroxide, form a paste that hardens quickly. This material was given the name geopolymer, which is a material with high mechanical strength and durability [4], characteristics that make it suitable for structural applications. Furthermore, when compared to materials produced from Portland cement, geopolymeric materials are not subject to carbonation and, in general, have high inertia, chemical stability and high fire resistance [7].

The use of geopolymers in ordinary Portland cement can reduce overall CO_2 emissions by 9% to 64%, depending on the raw material used and its geographic location, the use of silicates, the type of transportation, the place of sale and manufacture of the alkaline activator, and the conditions for preparing the mixture [8].

Despite the environmental and structural advantages of geopolymers [7], their technology is still relatively new and lacks standardization for its safe application in civil construction. Among the different techniques for analyzing Portland cement concrete that are consolidated in the scientific community, non-destructive tests stand out, such as ultrasonic wave propagation analysis. This method stands out for its practicality and efficiency in evaluating properties such as density, homogeneity, and mechanical strength, without compromising the integrity of the structure. This non-destructive analysis, already regulated in applications with Portland cement concrete, can also be an alternative for evaluating geopolymer concreting [2,9,10,11]. However, its use in geopolymers lacks specific regulation, since international guidelines, such as ASTM C 597: 20021 [12] and EN 12504-4 [13], were developed for Portland cement-based concretes and do not yet contemplate the particularities of geopolymeric materials.

he Brazilian standard NBR 8802: Hardened concrete – Determination of ultrasonic wave propagation speed [14], for example, regulates the use of ultrasound in hardened Portland cement concrete. However, there is still no equivalent standard for the analysis of geopolymers, which creates a regulatory vacuum and highlights the need for more research and specific tests to establish appropriate parameters for the application of this technology in these materials. The possibility of using consolidated ultrasound methods reliably in geopolymers would represent a significant advance for the construction industry, both in improving the quality of buildings and in promoting environmental sustainability.

Some authors [2,10,15,11] have used the technique of analyzing the propagation speed of ultrasonic waves as a parameter for characterizing geopolymeric materials, thus contributing to the increase in the collection of comparative data and to the reliability of the use of this technique. Despite the potential interferences resulting from its high detection sensitivity, the method has demonstrated reliability, as long as it is applied with prior knowledge of the characteristics of the samples, as evidenced in previous studies [2]. In some studies [2,11] it was found that, due to the high correlation observed, ultrasonic testing can assist or even replace compression strength tests in analyzing the evolution of cement paste hydration or geopolymerization reactions in concrete. Furthermore, considering the need for a medium to propagate ultrasonic waves, this technique can be effectively used as a tool for assessing concrete quality, enabling the detection of flaws, cracks, and other physical characteristics [11].

In this context, with the aim of investigating the application of the ultrasonic wave propagation technique, this study produced geopolymer samples from metakaolin as a precursor material and sodium hydroxide solutions as an activating agent. An experimental model was developed to evaluate the influence of the proportions of the materials and the use of sodium silicate on the following parameters: ultrasonic wave propagation speed, axial compressive strength and physical properties, such as specific mass and water absorption. For each of these characteristics, response surfaces were generated, allowing a detailed analysis of the combined effects of the variables studied.

II. MATERIALS AND METHODS

To carry out the study, the methodology was divided into the following parts: a) characterization of the raw materials; b) preliminary tests of paste consistency and 1st data entry for experimental modeling; c) preparation of the solutions; d) preparation of the pastes and molding of the test specimens; f) curing of the test specimens; g) tests: ultrasonic, resistance and physical analysis and h) 2nd data entry in the experimental modeling, as shown in Figure 1.

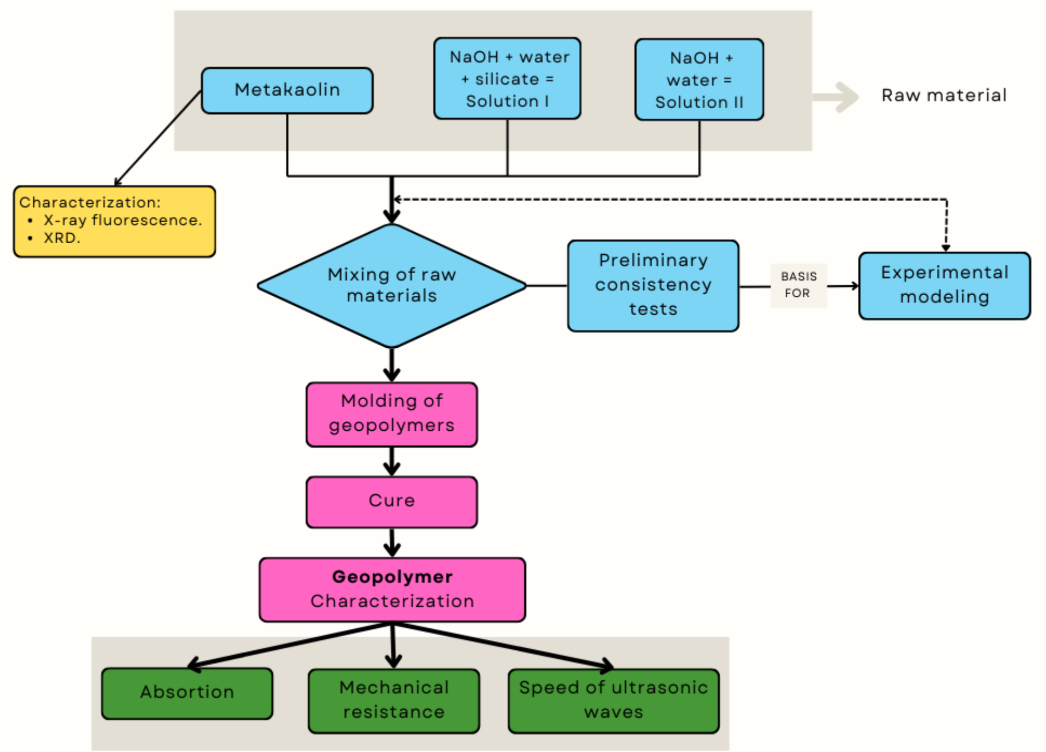

Figure 1. Methodology flowchart.

2.1. Characterization of raw materials

The raw materials used in the production of the geopolymer samples were: metakaolin, sodium hydroxide, sodium silicate and water.

To characterize the metakaolin, X-ray fluorescence and X-ray diffraction (XRD) techniques were used. These techniques were used to quantify the oxides present in the sample and to verify the crystalline structure, since the SiO_2/Al_2O_3 molar ratio and amorphicity are factors that interfere in the geopolymerization reactions.

Through X-ray fluorescence analyses, the percentages of the SiO_2 and Al_2O_3 compounds were obtained, which are 57.0% and 34.0%, respectively. From these results, it was possible to calculate the molar ratios of the pastes, considering the literature data as a reference [4,8].

The sodium silicate used was from the Sulfal brand with the following compositions: 15% Na_2O and 33% SiO_2 and 52% H_2O. After characterizing the raw materials, preliminary tests were performed to define the input data in the experimental modeling program and obtain the traces of the geopolymer pastes, since the most important statistical activity is the planning of the experiments [16]. When this is not done appropriately, the result often generates sterile numbers, not allowing any conclusions. It is essential to define the factors and responses of interest in order to choose the most appropriate planning [17]. In addition, one must have an idea about the methods of processing the results to avoid systematic errors and validate the results.

2.2. Preliminary paste consistency tests and 1st stage of data entry for experimental modeling

The first step in the preliminary tests was to determine the amount of metakaolin (800 g), based on the minimum volume required to fill the specimens that would be molded. Then, paste consistency tests were performed. For these tests, random amounts of water were added, starting from the minimum value of 316 g and other amounts of water were randomly added up to the maximum value of 384 g to the sodium hydroxide (also a random value) and to the metakaolin, in order to obtain pastes whose consistencies allowed the molding of the specimens.

In view of the results obtained in the preliminary tests and in literature [4,8], the input data for the 1st stage of the experimental modeling were defined using the Minitab® 21.1.1 2022 software. Table 1 presents the input data for the 1st stage of the experimental modeling.

Table 1. Input data for experimental modeling.

Values	*Silicate Mass (g)	**NaOH mass (g)	Water mass (g)	Metakaolin mass (g)	***SiO_2/Al_2O_3 ratio	****Na_2O/SiO_2 ratio
Minimum value	0	50	316	800	2.85	0.12
Maximum value	320	216	385	800	3.51	0.37

*The maximum and minimum values of the amounts of sodium hydroxide, the SiO_2/Al_2O_3 and Na_2O/SiO_2 ratios were defined using literature data.

**The amount of sodium silicate was defined by calculating its solubility in the minimum amount of water.

Through the 1st experimental modeling, 14 combinations of proportions of the raw materials were obtained, as can be seen in Table 2.

In order to evaluate the interference of the use of silicate in the geopolymer samples, two dosage blocks were defined for the modeling of the 14 samples, as shown in Table 2. For Block I, the samples were considered without the addition of sodium silicate, while for Block II the samples contained sodium silicate in their composition. The amount of solid silicate in the Block II samples was 320 g with the aim of increasing the SiO_2/Al_2O_3 molar ratio of the mixture to a maximum value of silicate solubility given the minimum amount of water used (316 g) and thus ensuring molding consistency based on preliminary tests.

From the 14 combinations, two types of sodium hydroxide and water solutions (solution I) were prepared for the Block I samples (7 tests) and sodium hydroxide, water and sodium silicate solutions (solution II) for the Block II samples (7 tests). It is worth noting that all tests were performed in duplicate.

Table 2. Composition of geopolymer pastes from the experimental model.

Order of the test	Blocks	Silicate Mass (g)	NaOH mass (g)	Water mass (g)	Metakaolin mass (g)
1	1	0.00	133.00	350.00	800
2	1	0.00	74.31	325.96	800
3	1	0.00	191.69	374.04	800
4	1	0.00	133.00	350.00	800
5	1	0.00	191.69	325.96	800
6	1	0.00	133.00	350.00	800
7	1	0.00	74.31	374.04	800
8	2	320.00	133.00	384.00	800
9	2	320.00	133.00	350.00	800
10	2	320.00	50.00	350.00	800

11	2	320.00	133.00	316.00	800
12	2	320.00	133.00	350.00	800
13	2	320.00	216.00	350.00	800
14	2	320.00	133.00	350.00	800

2.3. Preparation of solutions for molding blocks I and II

After defining the features of the pastes through the first stage of experimental modeling for block molding, two types of solutions were prepared – solution I and solution II – with different concentrations, as can be seen in Figures 2 and 3.

Solution I had sodium hydroxide as the solute and water as the solvent and was prepared in seven concentrations for Block I, as can be seen in Table 2. It was prepared 24 h before molding the geopolymer samples. Solution II had sodium hydroxide and sodium silicate as the solutes and water as the solvent. They were also prepared in seven concentrations for molding Block II. Solution II was prepared 48 h before molding the samples so that the sodium silicate in flakes could react and stabilize the temperature of both solutions.

Figure 2. Solution I: containing sodium hydroxide and water.

Figure 3. Solution II: containing sodium hydroxide, silicate and water.

2.4. Preparation of the paste and molding of the test specimens

To prepare the geopolymer paste for different mixes, the metakaolin was added to the mixer, then either solution I or solution II, depending on the block to be molded. The timer was activated to standardize the mixing process. Next, the mixer was turned on at speed 1 and left for 2 minutes, then its edges were scraped with a spatula and turned on again for 3 more minutes. After the second stop, the sides of the container were scraped again and mixed at speed 2 for another 2 minutes. Part of the paste was poured into 5 cm x 10 cm cylindrical molds to cure and then check the propagation speed of ultrasonic waves and analyze the mechanical strength. Another part of the paste was poured into aluminum capsules to also perform physical analyses after curing.

2.5. Curing of test specimens

For curing, all samples were placed in an oven at 45 °C, remaining in the molds for 72 h and then removed for demolding. The samples were then placed back in the oven for final curing for 15 days. Hot curing was adopted to stabilize the temperature and accelerate the geopolymerization reactions.

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After curing, the specimens and capsules were wrapped in plastic film to maintain humidity until the tests were performed, namely: ultrasonic wave propagation speed, compressive strength, specific mass and water porosity.

2.6. Ultrasonic testing

The ultrasonic test was performed in accordance with the Brazilian standard ABNT NBR 8802: 2019 [14], using the Tico model ultrasound device from Proceq. The direct measurement method was used with transducers at the ends of the test specimens as shown in Figure 4. The samples were supported on wooden slats to minimize possible interference.

Figure 4. Application of the ultrasonic wave method in geopolymer samples.

2.7. Mechanical resistance test

The compressive strength evaluation test was performed after rectification of the samples, and performed according to the descriptions of NBR 7215: 2019 – Portland Cement – Determination of compressive strength of cylindrical test specimens [18], as shown in Figure 5. The equipment for the compressive strength test was a universal testing machine, Emic brand, with a loading speed of 0.3 MPa/s.

Figure 5. Axial compression test.

2.8. Physical tests

The physical characterization tests (specific mass and porosity) for the capsule samples were performed in accordance with NBR NM 53 Coarse aggregate – Determination of specific mass, apparent specific mass and water absorption [19]. After curing the geopolymer samples, they were weighed (M), then submerged in water for 24 hours. After this period, their surfaces were dried with a cloth until the saturated dry surface condition (Ms) and, subsequently, each sample was placed in the wire basket, immersed and hydrostatic weighing was performed. To calculate the specific mass, Equation 1 was used.

$$d_s = \frac{M_s}{M_s - M_a} \tag{1}$$

Water absorption was calculated from Equation 2.

$$A = \frac{M_s - M}{M_s} \tag{2}$$

2.9. Second data entry in the experimental model

Based on the results obtained through the ultrasonic wave propagation speed and compressive strength tests, and the data on the compositions of the test specimens, Minitab® 21.1.1 2022 software was used again for a 2nd data entry into the experimental model, in order to obtain the response surfaces of the following properties: ultrasonic wave propagation speed, compressive strength, specific mass and water porosity. For the hypothesis tests, a significance level (α) of 5% was adopted.

III. RESULTS

The preliminary tests allowed the definition of the amount of water that would allow the molding of the test specimens based on the consistency of the paste. The values of the minimum and maximum volumes of water were 316 mL and 384 mL, respectively, which were used to feed the experimental model. It was observed that when the amount of water was lower than the minimum value, the mixtures had a dry appearance and it was not possible to mold them. However, when the amount of water was higher than the maximum value, the paste had a fluid consistency that made it impossible to thicken and consequently to mold it.

In the experimental model, according to the methodology, after the 2nd data entry into the program and the output variables were defined, namely: ultrasonic wave propagation speed, compressive strength and physical properties, the response surfaces were generated.

As can be seen in Table 1, the use of sodium silicate in the samples of Block 1 to evaluate the propagation speed of ultrasonic waves, considering the significance level of 5%, was significant, since the value of the calculated probability (p) obtained was 0.002, that is, it was less than 0.05 (p_0), thus, the null hypothesis (H_0) is rejected. It is known that the molar ratios of the oxides of the raw materials influence the mechanical resistance of the geopolymer materials [4]. However, the ranges of molar ratios of the sodium hydroxide and water compounds adopted in this work, Table 1.

Table 1. Coefficients of the response surface of propagation velocity of ultrasonic waves versus NaOH and water.

Term	Coeff.	P-Value
Block 1 (with silicate)	6.00	0.002
NaOH (g)	1.50	0.385
H_2O (g)	0.16	0.922
NaOH (g)*NaOH (g)	-0.71	0.687
H_2O (g)*H_2O (g)	-2.21	0.231
NaOH (g)*H_2O (g)	3.50	0.170

The contour surface of the ultrasonic wave propagation velocity parameter for the test specimen samples can be seen in Figure 6. It should be noted that the quantitative evaluation of the influence of the use of sodium silicate was not considered in the model. As presented in the methodology, the data entry through blocks (with and without sodium silicate) was performed only to verify qualitatively whether the presence of sodium silicate would influence the physical and mechanical properties of the geopolymer pastes.

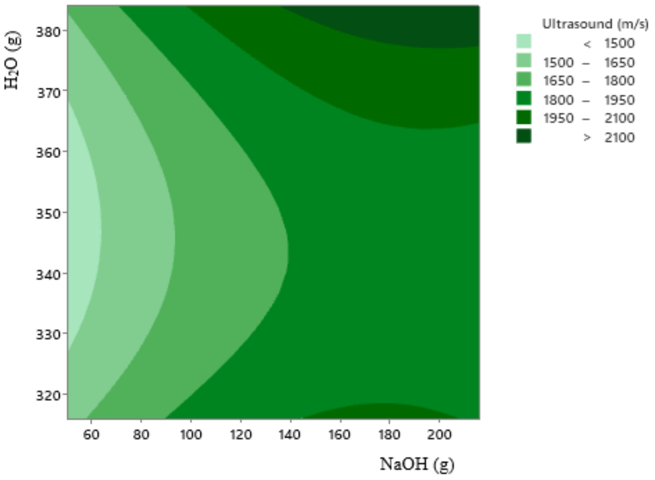

Figure 6. Contour plot of ultrasonic wave propagation speed vs. water vs. NaOH.

The response surface of the compressive strength parameter is shown in Figure 7.

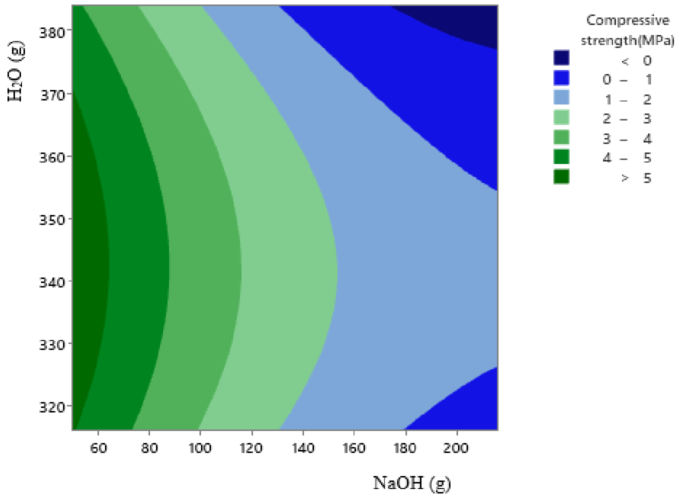

Figure 7. Contour plot of compressive strength vs. water vs. NaOH.

It can be seen from Figures 6 and 7 that the increase in sodium hydroxide consumption influenced the increase in the propagation speed of ultrasonic waves and the decrease in compressive strength. It was also found that in the compressive strength ranges between 2 and 5 MPa, the amount of water did not influence the resistance. For the mechanical resistance ranges between 0 and 1 MPa (Figure 7), the increase in the amount of sodium hydroxide interfered with water consumption, and consequently with the compressive strength of the samples. It is suggested that the excess and lack of water affected the chemical reactions of geopolymerization, preventing the agglomeration of particles, dispersing them (excess of water) or preventing the complete chemical reaction (lack of water).

As shown in Figure 7, the highest ultrasonic wave speeds were observed in the region with low mechanical resistance (0 – 1 MPa) and water consumption above 350 mL (approximately) (Figure 6). This may have occurred due to the excess water present inside the sample, since the test specimens were wrapped in plastic, preventing excess water from escaping.

To assess the quality of Portland cement concrete, one of the references is the propagation speed of ultrasonic waves, as shown in Table 3. These values refer to concrete, which is composed of binder (Portland cement), water and aggregates. It is worth noting that the propagation speed of ultrasonic waves is affected by the aggregates contained in the concrete, which is different, therefore, from the speed found only in pastes. As geopolymer materials are characterized by having greater porosity in relation to Portland cement [20], the propagation speed range of ultrasonic waves, which require a medium to propagate, cannot be considered the same range to infer the quality of concreting for geopolymer materials.

Table 3. Classification of Portland cement concrete according to the propagation speed of the ultrasonic pulse.

Propagation speed (m/s)	Concrete conditions
Higher than 4500	Excellent
3500 to 4500	Good
3000 to 3500	Regular
2000 to 3000	Generally bad
Less than 2000	Bad

Fonte: Adapted [21].

The propagation of ultrasonic waves is also related to the specific mass of concrete. This relationship is one of the variables that provide the basis for its use in evaluating the resistance of the material under limit [22], since other variables such as type and proportion of constituent materials, humidity and temperature, also influence the pulse propagation speed.

Figure 8 shows the response surface of the specific mass as a function of the proportions of water and sodium hydroxide. It is noted that the specific mass does not follow the trend observed in the ultrasonic wave propagation speed diagram (Figure 6). This may have occurred because the less dense material tends to absorb more water. It is worth mentioning that, since extreme dosages were considered in this study (Table 1), some samples apparently did not undergo the complete geopolymerization process, as can be seen in Figures 9 and 10. Specimen 14, for example, was shown to be softened and deformable after the curing period. Marks were observed on the surface of the sample during the compressive strength test (Figures 9 and 10). After 7 months of curing, the presence of whitish material (silicate and sodium hydroxide) was noted on the surface of specimen 14 (Figure 11). This indicates that there was no chemical interaction between the precursor and the alkaline solution, unlike what was observed in sample 1 (Figure 12).

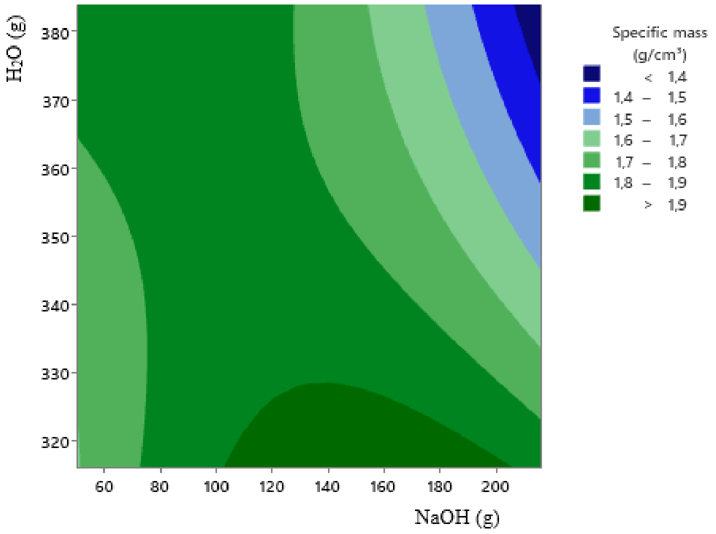

Figure 8. Contour plot of specific gravity vs. water vs. NaOH.

Figure 9. Test specimen 14 with a wet appearance.

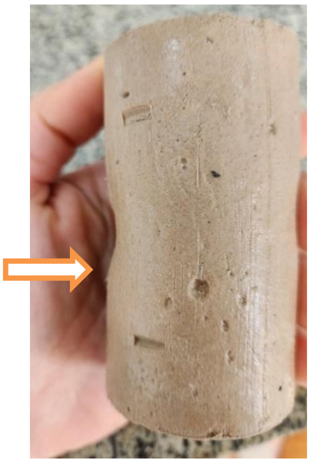

Figure 10. Finger mark on specimen 14.

Figure 11. Image of specimen 14 after seven months of curing.

Figure 12. Image of specimen 1 after seven months of curing.

Comparing the X-ray diffraction results of metakaolin (Figure 13) with those of sample 10 (Figure 15), which had a compressive strength of 0 MPa, similarities were observed, indicating that the geopolymer paste of sample 10 was not effective in the geopolymer reactions. However, as shown in Figure 14, sample 1, which presented 1.42 MPa of compressive strength, indicates that the metakaolin was consumed more due to the decrease in the intensity of the peak between 25 °C and 30 °C.

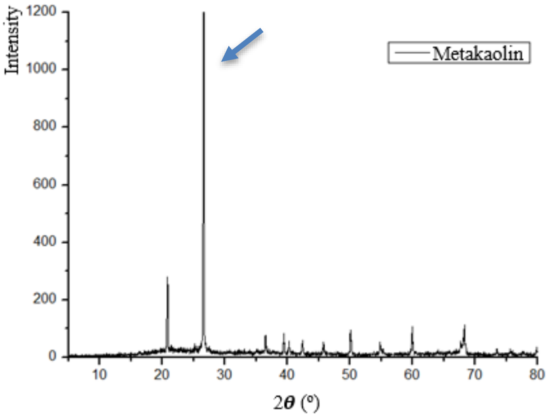

Figure 13. Diffractogram of the metakaolin sample.

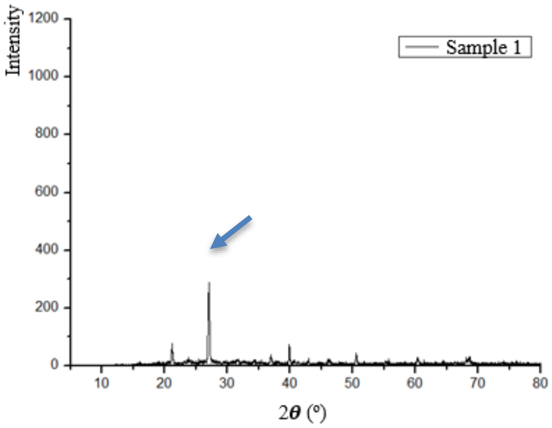

Figure 14. Diffractogram of sample 1 (1.42MPa).

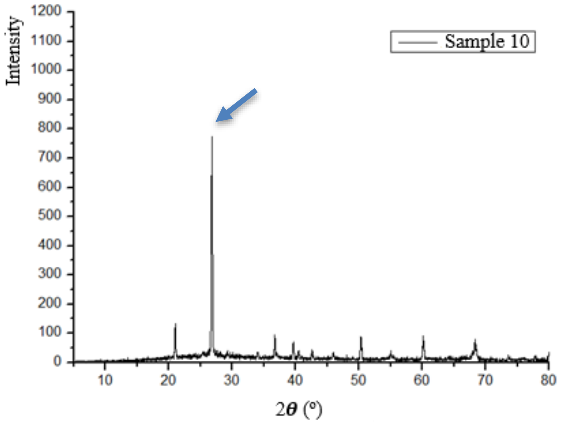

Figure 15. Diffractogram of sample 10 (0 MPa).

The variations in water absorption as a function of the proportions of the raw materials are shown in Figure 16. It can be seen that there was an increase in water absorption as the amount of NaOH increased and that the amount of water in the mixture did not influence the absorption between the sodium hydroxide concentration ranges of the geopolymers. As observed in Figures 6 and 7, in which the increase in sodium hydroxide consumption influenced the compressive strength and the speed of ultrasonic waves.

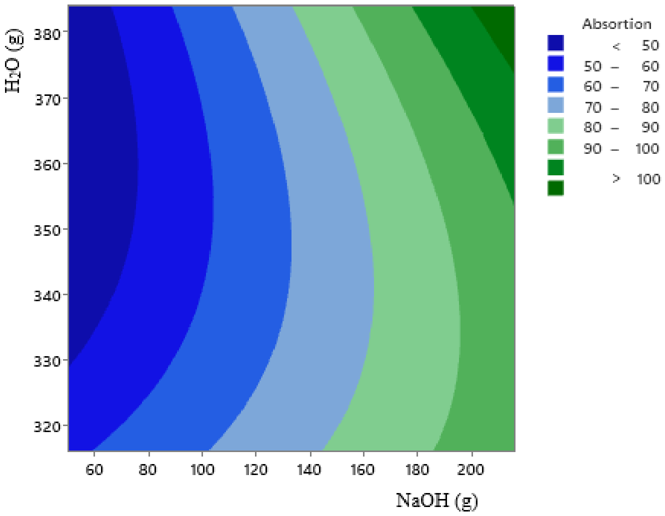

Figure 16. Contour plot of absorption of water and NaOH.

The transformation of the precursor liquid into a “solid” gel and the densification mechanisms are some of the most critical phases of geopolymerization, since the proportion of water can allow control of the nanostructure, porosity and properties of geopolymers so that they can be adapted for specific applications [5]. Furthermore, gelation results from the hydrolysis-polycondensation of aluminum and silicon contained in the raw materials, resulting in a complex network swollen by water trapped in the pores [5]. Thus, the chemical composition of the precursor and activators can affect the final properties of the material, which demonstrates the complexity of the geopolymerization process and emphasizes the need to use statistical tools to infer information about the process.

Although the samples were kept under similar curing and storage conditions, it is suggested that the constituent water, closed pore water and absorbed water significantly influenced the propagation speed of ultrasonic waves. This fact indicates that the use of the aforementioned non-destructive test is complex and that intrinsic and extrinsic variables must be considered and that further studies must be carried out.

IV. CONCLUSIONS

It is concluded that the use of the ultrasonic method, widely consolidated and standardized for Portland cement concretes, requires a more detailed approach for application in geopolymers, since the geopolymerization process depends directly on the proportion and type of chemical constituents present in the raw materials.

The results obtained demonstrated that the use of sodium silicate in geopolymer formulations can significantly influence the propagation speed of ultrasonic waves, considering the significance level of 5%, since the calculated probability value (p) obtained was 0.002, that is, it was less than 0.05 (p_0).

The propagation speed of ultrasonic waves can be influenced by several variables (raw materials, absorption, density), suggesting that the use of this non-destructive test in geopolymer materials requires additional studies to enable reliable inferences about the quality of the product.

The increase in sodium hydroxide consumption influenced the increase in the propagation speed of ultrasonic waves and in the decrease in compressive strength. In the compressive strength ranges between 2 and 5 MPa, the amount of water did not influence the resistance and, for the mechanical resistance ranges between 0 and 1 MPa, the increase in the amount of sodium hydroxide interfered in the water consumption, and, consequently, in the compressive strength of the samples.

In the region where there is low mechanical resistance (0 – 1 MPa) and water consumption above 350 mL (approximately), the highest ultrasonic wave speeds were observed.

The ranges of molar ratios of the sodium hydroxide and water compounds adopted in this work did not allow their variations to be correlated with the following properties: compressive strength and ultrasonic wave propagation speed, considering a significance level of 5%.

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REFERENCES

[1] L. S. Borges, P. H. R., Lourenço, T. M. D. F., Foureaux, A. F. S., & Pacheco, “*Estudo comparativo da análise de ciclo de vida de concretos geopoliméricos e de concretos à base de cimento Portland composto (CP II)*,” Ambiente Construído, pp. 153–168, 2014.

[2] M. Rahmati, V. Toufigh, and K. Keyvan, “*Monitoring of crack healing in geopolymer concrete using a nonlinear ultrasound approach in phase-space domian*,” Ultrasonics, vol. 134, no. 107095, 2023.

[3] S. N. da I. do Cimento, “*Dados do setor de cimento Portland*” 2023. http://snic.org.br/ (accessed Nov. 20, 2023).

[4] J. Davidovits, *Geopolymer: Chemistry and Applications*. Saint-Quentin, France, 2011.

[5] K. Komnitsas and D. Zaharaki, "*Geopolymerisation: A review and prospects for the minerals industry*" Miner. Eng., vol. 20, no. 14, pp. 1261–1277, 2007, doi: 10.1016/j.mineng.2007.07.011.

[6] C. Kaya, M., Uysal, M., Yilmaz, K., & ATİŞ, "*Behaviour of geopolymer mortars after exposure to elevated temperatures*," Mater. Sci. - Medzg., vol. 24, 2018.

[7] J. Davidovits, "Green Chemitry and Sustainable Development Solutions," Institute Géopolymère. Saint-Quentin, France, 2005.

[8] J. Matsimbe, M. Dinka, D. Olukanni, and I. Musonda, "*Geopolymer: A Systematic Review of Methodologies*," Materials (Basel)., vol. 15, no. 19, pp. 1–34, 2022, doi: 10.3390/ma15196852.

[9] M. Sitarz, I. Hager, and M. Choińska, "*Evolution of mechanical properties with time of fly-ash-based geopolymer mortars under the effect of granulated ground blast furnace slag addition*," Energies, vol. 13, no. 5, 2020, doi: 10.3390/en13051135.

[10] O. Gencel, A. Gholampour, H. Tokay, and T. Ozbakkaloglu, "*Replacement of natural sand with expanded vermiculite in fly ash-based geopolymer mortars*," Appl. Sci., vol. 11, no. 4, pp. 1–18, 2021, doi: 10.3390/app11041917.

[11] R. Occhipinti *et al.*, "*Structural properties of volcanic precursors-based geopolymer before and after natural weathering*," Ceram. Int., vol. 49, pp. 21892–21902, 2023.

[12] American Society for Testing and Materials, "*ASTM C 597 - Standard Test Method for Pulse Velocity Through Concrete*." In: Annual Book of ASTM Standards, 2022.

[13] European Standards, "*EN 12504-4 - Testing concrete in structures: Determination of ultrasonic pulse velocity."* European Standard, 2021.

[14] Associação Brasileira de Normas Técnicas, "*NBR 8802 - Concreto endurecido - Determinação da velocidade de propagação de onda ultrassônica*." Rio de Janeiro, 2019.

[15] H. Y. Zou, W. L. Zhong, X. Zhao, and L. F. Fan, "*Optimizing geopolymer mortar for shotcrete applications by focusing on flowability and early-age mechanical characteristics*," Constr. Build. Mater., vol. 418, no. January, 2024, doi: 10.1016/j.conbuildmat.2024.135290.

[16] R. E. Neto, B. B.; Scarminio, I. S.; Bruns, *Como Fazer Experimentos Pesquisa e Desenvolvimento na Ciência e na Indústria*. Campinas, 2001.

[17] D. C. Myers, R.H., Montgomery, *Response Surface Methodology*, 2ª. 2002.

[18] Associação Brasileira de Normas Técnicas. "*NBR 7215 Cimento Portland - Determinação da resistência à compressão de corpos de prova cilíndricos.*" Rio de Janeiro, 2019.

[19] Associação Brasileira de Normas Técnicas, "*ABNT NM 53 - Agregado Graúdo - Determinação de Massa Específica, Massa Específica Aparente e Absorção de Água*." Rio de Janeiro, 2009.

[20] S. M. A. Qaidi *et al.*, "*Ultra-high-performance geopolymer concrete: A review*," Constr. Build. Mater., vol. 346, no. March, p. 128495, 2022, doi: 10.1016/j.conbuildmat.2022.128495.

[21] L. A. F. Bauer, *Materiais de construção*, 6th ed. Rio de Janeiro: 1, 2019.

[22] A. M. Neville, *Propriedades do concreto*, 5th ed. Porto Alegre: Bookman, 2016.

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