

**INSTITUTO TECNOLÓGICO DE AERONÁUTICA**



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**DESENVOLVIMENTO DE CIMENTO ATIVADO  
ALCALINAMENTE MONOCOMPONENTE COM  
PRECURSORES SÓLIDOS DE BAIXO TEOR DE  
CÁLCIO E FONTES ALCALINAS ALTERNATIVAS.**

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# **DESENVOLVIMENTO DE CIMENTO ATIVADO ALCALINAMENTE MONOCOMPONENTE COM PRECURSORES SÓLIDOS DE BAIXO TEOR DE CÁLCIO E FONTES ALCALINAS ALTERNATIVAS.**

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São José dos Campos: maio 26, 2025.

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*"If I have seen farther than others,  
it is because I stood on the shoulders of giants."*

— SIR ISAAC NEWTON

# Resumo

Na busca por alternativas mais sustentáveis ao cimento Portland, os cimentos ativados alcalinamente têm sido amplamente estudados. No entanto, a maioria dos processos de mistura ocorre em duas etapas, o que impacta a viabilidade e a eficiência construtiva. Um avanço importante nessa área é o desenvolvimento de sistemas monocomponentes, que simplificam a produção e tornam a tecnologia mais acessível e prática. Ainda assim, os estudos atuais se concentram em precursores ricos em cálcio, enquanto o uso de fontes alcalinas tradicionais apresenta desafios relacionados à segurança e ao custo. Este trabalho propõe o desenvolvimento de um cimento ativado alcalinamente monocomponente utilizando precursores sólidos de baixo teor de cálcio, como sílica ativa e metacaulim, e fontes alcalinas mais seguras e acessíveis, como carbonato de potássio e hidróxido de cálcio, garantindo resistência mecânica adequada e maior viabilidade para aplicação na construção civil.



# Abstract

In the search for more sustainable alternatives to Portland cement, alkali-activated cements have been extensively studied. However, most mixing processes occur in two separate steps, limiting their feasibility and constructive efficiency. A significant advancement in this field is the development of one-part (just-add-water) systems, which simplify production and make the technology more accessible and practical. Nonetheless, current studies mainly focus on calcium-rich precursors, while the use of conventional alkaline activators raises concerns related to safety and cost. This work proposes the development of a one-part alkali-activated cement using low-calcium solid precursors, such as silica fume and metakaolin, along with safer and more affordable alkaline sources, such as potassium carbonate and calcium hydroxide. The goal is to ensure adequate mechanical performance while enhancing the viability of these materials for application in the construction industry.

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# List of Abbreviations and Acronyms

$CO_2$	carbon dioxide
GHG	greenhouse gases
AAM	alkali-activated materials
$SiO_2$	silica
$Al_2O_3$	alumina
N-A-S-H	sodium aluminate silicate hydrate
C-A-S-H	calcium aluminate silicate hydrate
$K_2CO_3$	potassium carbonate
$Ca(OH)_2$	calcium hydroxide
MK	metakaolin
SF	silica fume
IPT	Institute for Technological Research
ITA	Aeronautics Institute of Technology
EDS	Energy dispersive X-ray spectroscopy
XRD	X-ray diffraction
$OH^-$	hydroxyl
FTIR	Fourier transform infrared spectroscopy
ABNT	Brazilian Association of Technical Standards
NBR	Brazilian Standard
ASTM	American Society for Testing and Materials
OPC	Ordinary Portland Cement
GGBFS	Ground Granulated Blast Furnace Slag
MSWIA	Municipal Solid Waste Incineration Ash
NaOH	sodium hydroxide
$Na_2SiO_3$	sodium silicate
KOH	potassium hydroxide
$Na_2CO_3$	sodium carbonate

# List of Symbols

$a$	Distance
$\mathbf{a}$	Distance vector
$\mathbf{e}_j$	Unit vector of dimension $n$ with the $j$ -th component equal to 1
$\mathbf{K}$	Stiffness matrix
$m_1$	Termite mass
$\delta_{k-k_f}$	Kronecker delta at instant $k_f$

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# 1 Introduction

Cement is one of the main materials in civil construction, being used from the construction of houses and buildings to bridges and highways. In developing countries such as Brazil, cement is widely used due to its low complexity and cost, which allows its use on a large scale in any location. The exponential increase in cement production, 10 times greater than the world population growth (United Nations, 1995), has been accompanied by a significant share of greenhouse gas (GHG) emissions, due to the calcination process of limestone that transforms calcium carbonate into calcium oxide and carbon dioxide in high-temperature furnaces. The production of Portland cement generates on average 842 kg of  $CO_2/t$  of clinker produced (ANDREW, 2018), representing 5% of anthropogenic GHG emissions (IEA; WBCSD, 2009).

In this context, there is a need to develop new cementitious materials that present three main properties: low GHG emissions, low cost, and high strength/durability (SCRIVENER *et al.*, 2018).

Alkaline-activated materials (AAM) - solid precursors rich in silica ( $SiO_2$ ) and alumina ( $Al_2O_3$ ), capable of forming binding gels composed of sodium-alumino-silicate hydrate (N-A-S-H) and calcium-alumino-silicate hydrate (C-A-S-H) - have gained prominence due to their potential to partially or totally replace Portland cement, significantly reducing the GHG emissions associated with conventional cement production.

There are two ways in which AAM can be produced: by mixing the solid precursor with a liquid alkaline activator, or with a solid alkaline source and water. Two-part systems have been widely employed in the initial development of this market due to their high mechanical performance, durability, and chemical resistance. However, one-part systems are a more scalable technology due to the lower risk of handling and storing of solid activators (PROVIS, 2018).

Calcium-rich solid precursors are more used for several factors, such as the rapid strength gain (PROVIS; BERNAL, 2014), less dependence on thermal curing (KE *et al.*, 2021), and the fact that C-A-S-H reaction products tend to form a denser and less porous matrix than N-A-S-H gels (BERNAL *et al.*, 2014). In this sense, there is a technical and scientific gap in the formulation and characterization of low-calcium geopolymer monocomponents.



This work proposes the development of a one-component alkaline-activated cement focusing on low-calcium solid precursors, specifically metakaolin and silica fume, combined with safer and more accessible alternative alkaline sources, such as potassium carbonate ( $K_2CO_3$ ) and calcium hydroxide ( $Ca(OH)_2$ ). This approach aims to contribute to the formulation of more sustainable, safe, and adequately performing binders for applications in civil construction, aligning with contemporary guidelines for low environmental impact (POLÍTICA..., 2016).

## 2 Literature Review

### 2.1 Historical Context

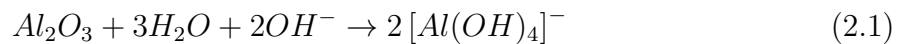
According to (PACHECO-TORGAL *et al.*, 2014), the synthesis of materials by alkali activation began in the 1930s and 1940s, when a substitute for traditional Portland cement was developed from blast furnace slag and other aluminosilicates. From the 1970s onwards, interest in this area increased, when the French scientist Joseph Davidovits coined the term "geopolymer" and patented several formulations. His initial studies focused on the development of inorganic, non-flammable, and fire-resistant materials (PROVIS; DEVENTER, 2009).

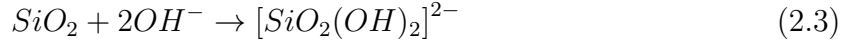
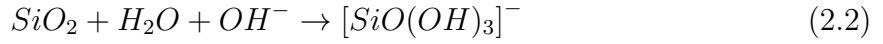
Since then, alkali-activated materials (AAM) have attracted the attention of researchers and industry due to their low energy consumption and sustainable nature (QIN *et al.*, 2022). Furthermore, as studies have advanced, AAMs have gained recognition for their mechanical properties and durability, as the polymerization reactions that occur during curing provide high compressive strength and resistance to chemical attack.

### 2.2 Raw Materials for AAM

#### 2.2.1 Precursors

Precursors are materials rich in  $SiO_2$  and  $Al_2O_3$  that, when activated by an alkaline solution, form a three-dimensional network of aluminosilicates (RAKHIMOVA; RAKHIMOV, 2019). The mechanical and kinetic properties of AAMs are strongly influenced by the  $SiO_2/Al_2O_3$  ratio (PROVIS, 2007). The initial activation process involves the dissolution of aluminosilicates through the breaking of covalent bonds  $Si - O - Si$  and  $Al - O - Al$  in a high pH environment (SEVERO *et al.*, 2013). Hydrolysis can be represented as follows:





Subsequently, the dissolved silicates and aluminates react with each other, forming a gel that undergoes polymerization and hardening processes, as illustrated in Figure 2.1.

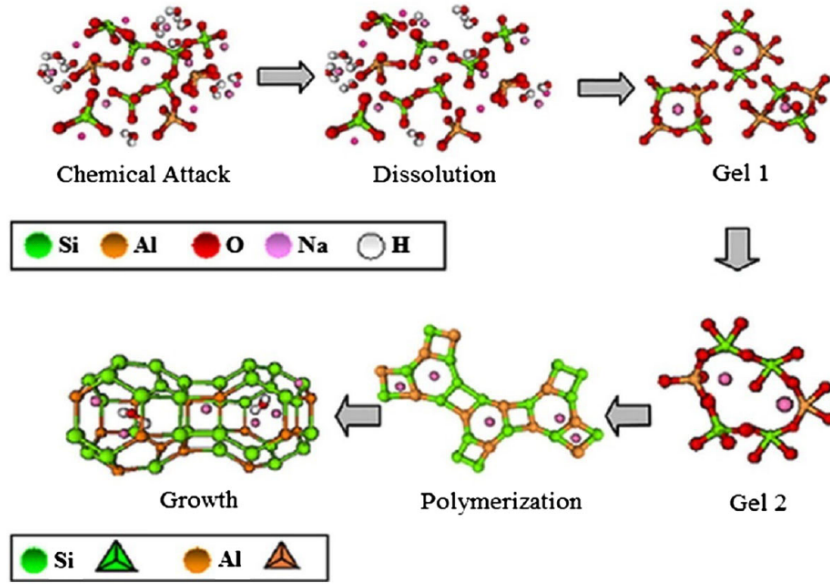


FIGURE 2.1 – Scheme of the alkaline activation process (DUXSON A. FERNÁNDEZ-JIMÉNEZ, 2006).

Precursors can be divided into two categories: those with high calcium content, such as blast furnace slag and fly ash, and those with low calcium content, such as metakaolin. Figure 2.2 shows the most common precursors and their respective chemical compositions.

The first group primarily produces calcium aluminate silicate hydrate (C-A-S-H) as a result of the activation reaction, while the second group predominantly forms sodium aluminosilicate hydrate (N-A-S-H) gel.

When the calcium levels in these precursors are high, the final product is a gel with rapid curing and high initial strength. However, these systems are more susceptible to shrinkage, cracking, and corrosion due to chloride attack. On the other hand, low-calcium systems form an tetrahedral amorphous network, which exhibits low permeability and shrinkage, better fire resistance, and a less porous structure. The  $\text{SiO}_2/\text{Al}_2\text{O}_3$  ratio is responsible for the degree of polymerization of the formed gel; therefore, if the ideal ratio is not achieved, the mechanical strength and durability of the AAM may be compromised. Finally, the N-A-S-H gel requires a longer curing time and a temperature between 80 – 100 °C to reach the appropriate mechanical strength (NODEHI; TAGHVAEE, 2022).

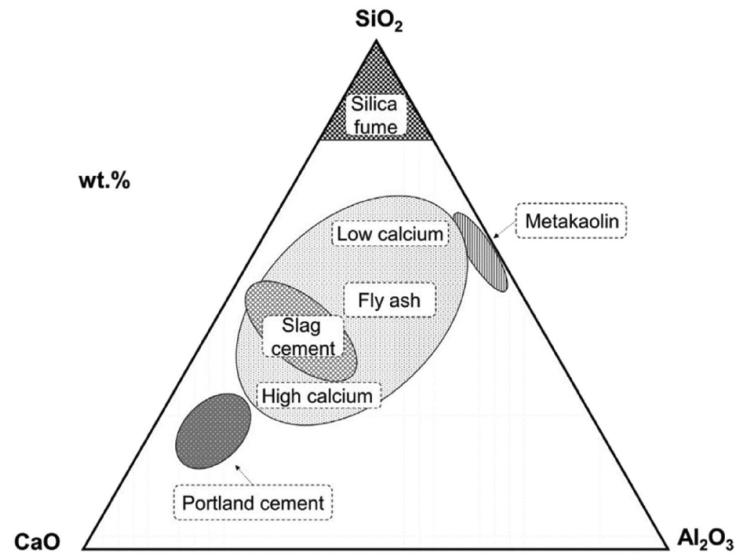


FIGURE 2.2 – Ternary diagram of the most common precursors (GIERGICZNY, 2019).

Table 2.1 presents the main characteristics of the most common precursors.

TABLE 2.1 – Characteristics of common or innovative residual materials that can be added to concrete to produce more sustainable binders (NODEHI; TAGHVAEE, 2022).

Additive name	Usual form	Average density (kg/m <sup>3</sup> )	Average particle size (µm)	Limitations	Benefits
Portland cement (OPC)	Irregular and angular	1440	0.15–20	–	–
Silica fume	Spherical	2200	0.1–0.5	Reduces workability and initial strength	Increases compactness, mechanical strength, and durability
Ground granulated blast furnace slag (GGBFS)	Angular with rough surface	1000–1300	1.25–250	Low initial strength	Increases durability, improves ITZ, and sulfate resistance
Fly ash	Spherical	540–860	0.5–300	Low initial strength	Improves workability and long-term strength
Metakaolin	Porous, lamellar, and angular	890	1–20	Reduces workability	Fills microstructure and improves ITZ
Rice husk ash	Irregular with high porosity	504–700	5–10	Property variation and low reactivity	High silica content; improves compactness and strength
Glass powder	Irregular	2500	0.8–50	High contamination	Improves durability and pozzolanic reaction
Red mud	Irregular and needle-shaped	2700–3400	100 to over 200	High contamination	High alumina content, can improve hydration
Ceramic waste	Angular	1700	Below 100	–	Improves compactness and performance
Municipal solid waste incineration slag (MSWI)	Irregular	660–1690	–	–	Improves microstructure and reduces porosity
Paper sludge ash	Irregular	Below 100	–	–	Favourably adjusts the S/A ratio

### 2.2.2 Activators

The alkaline attack on the microstructure of the precursors results in the release of silicates and aluminates into the solution. The solubility of silica and alumina as a function of pH is presented in Figure 2.3.

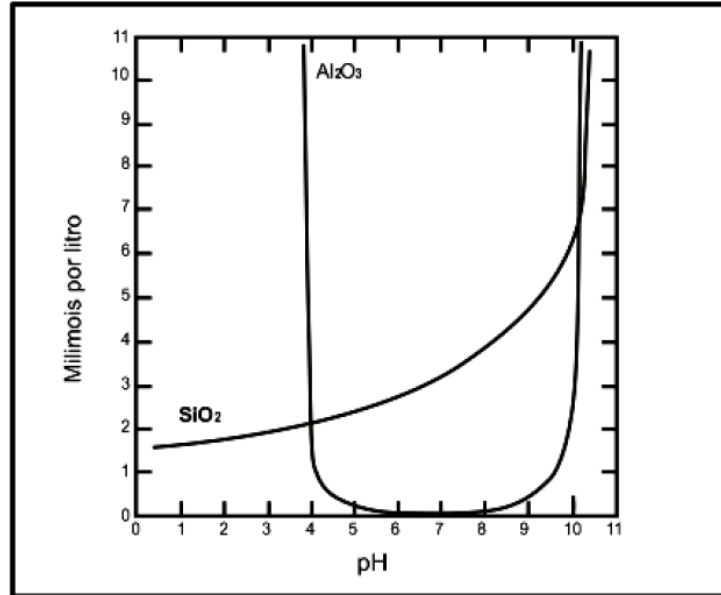


FIGURE 2.3 – Solubility of silica and alumina as a function of pH (MASON, 1952).

It is observed that the solubility of silica is low in acidic environments and high in basic media, while alumina is soluble at both extremes of pH. Therefore, for the activation reactions to occur, it is necessary that the pH of the solution is high.

Alkaline activators can be found in two forms: liquid—producing two-part geopolymers—or solid—one-part geopolymers. The main liquid alkaline activators are: sodium hydroxide ( $NaOH$ ), sodium silicate ( $Na_2SiO_3$ ), potassium hydroxide ( $KOH$ ), sodium carbonate ( $Na_2CO_3$ ), potassium carbonate ( $K_2CO_3$ ), and potassium oxide ( $K_2O$ ). The first studies on AAM focused on liquid activators, since the final product exhibits high compressive strength, adhesion, and the ability to withstand fatigue loads. In addition, they also demonstrate high resistance to freeze-thaw cycles and high temperatures (HEATH *et al.*, 2014).

Despite the advantages of two-part systems, basic solutions are corrosive and irritate human skin, making their transport and handling hazardous for workers (AWOYERA, 2019). Another point worth noting is that the production of sodium silicate occurs between  $1200 - 1400\text{ }^{\circ}C$  and emits approximately  $1.514\text{ kg}$  of  $CO_2$  per  $\text{kg}$  of silicate produced, in addition to significantly contributing to air pollution through dust and nitrogen and sulfur oxides (RAJAN, 2020).

Thus, one-part systems emerge as a safer alternative, since solid activators are less

hazardous and easier to handle. Even though one-part geopolymers exhibit lower mechanical strength and require thermal curing to achieve adequate performance (PROVIS, 2018), their use is more scalable.

## 2.3 Environmental Impacts

The main environmental advantage attributed to AAMs lies in the considerable reduction of  $CO_2$  emissions compared to traditional Portland cement. It is estimated that the environmental impacts of solid and liquid activators are 24% and 60% of the impact caused by OPC, respectively (LUUKKENEN Z. ABDOLLAHNEJAD, 2017). Furthermore, the production of AAMs often utilizes industrial residues as raw materials, such as blast furnace slag, sewage sludge ash, rice husk ash, sugarcane straw ash, among others (MORAES *et al.*, 2024). Therefore, in addition to the valorization of industrial waste, the production of AAMs reduces the demand for natural resources from mineral deposits and provides an environmentally appropriate destination, following the guidelines of the National Solid Waste Policy (POLÍTICA..., 2016).

## 2.4 Mechanical Properties

## 3 Methodology

### 3.1 Materials and Characterization

For the development of one-part geopolymeric mortars, the following components were used:

- Metakaolin (MK) supplied by the company XXX;
- Silica fume (SF) supplied by the company XXX;
- Potassium carbonate supplied by the company XXX;
- Calcium hydroxide supplied by the company XXX;
- standardized quartz sand supplied by the company XXX;
- Distilled water.

The binders used were silica fume and metakaolin. However, the purity of commercially available metakaolin is not sufficient to ensure precision in the characterization of cementitious samples. Therefore, it was produced from commercial kaolin, as detailed in Section 3.2. The alkaline sources are commercially available with high purity, so the physicochemical composition provided by the manufacturer was used.

The chemical composition of the materials used in the formulation of the mortars is presented in Table 3.1.



TABLE 3.1 – Chemical properties of the solid reagents.

Material	Chemical composition	Specification (%)
Silica fume	$SiO_2$	XX,X
	$Al_2O_3$	XX,X
	$MgO$	XX,X
	$CaO$	XX,X
	$Fe_2O_3$	XX,X
Potassium carbonate	$K_2CO_3$	XX,X
Calcium hydroxide	$Ca(OH)_2$	XX,X

In addition, the quartz sand used follows the standards established by the Institute for Technological Research (IPT), as shown in Tables 3.2 and 3.3.

TABLE 3.2 – Results of physical and chemical requirements of standardized quartz sand.

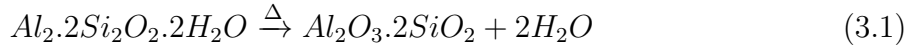
Property	Result	ABNT 7214:2015 Requirement	NBR Require- ment
Silica content (ABNT NBR 14656:2001)	96.5%	$\geq 95\%$ , by mass	
Moisture (ABNT NBR 7214:2015)	0.0%	$\leq 0.2\%$ , by mass	
Organic mat- ter (ABNT 17053:2022)	Lighter or equal to the color of the standard solution	Color of the 2% tannic acid standard solution	

TABLE 3.3 – Particle size distribution of the fractions of standardized quartz sand.

Fraction	Sieve interval	Mass percentage (%)		
		Result	ABNT 7214:2015 Requirement	NBR Re- quirement
16	(2.4 mm and 2.0 mm)	0	$\leq 10$	
16	(2.0 mm and 1.2 mm)	97	$\geq 90$	
30	(1.2 mm and 0.6 mm)	99	$\geq 95$	
50	(0.6 mm and 0.3 mm)	96	$\geq 95$	
100	(0.3 mm and 0.15 mm)	95	$\geq 95$	

## 3.2 Production of Metakaolin

Metakaolin was obtained by calcining kaolin at 700 °C for 1 hour in an electric furnace from XXX. The optimal calcination time and temperature were determined from preliminary tests, where the yield of calcination was evaluated. To ensure material homogeneity, two shallow trays with a maximum height of XX mm were used. The transformation of crystalline kaolinite into amorphous metakaolinite is represented by Equation 3.1.



## 3.3 Physicochemical Characterization of Solid Precursors

The physicochemical characterization of the solid precursors was carried out at the laboratories of the Aeronautics Institute of Technology (ITA), located in São José dos Campos-SP.

Energy-dispersive X-ray spectroscopy (EDS) was used to determine the proportion of chemical elements, performed together with scanning electron microscopy (SEM) to evaluate the morphology of the solid precursors.

In addition, X-ray diffraction (XRD) was used to determine the crystalline phase of metakaolin and silica fume.

To verify the removal of hydroxyl groups ( $OH^-$ ) and the presence of  $Al-Si-O$  bonds, Fourier-transform infrared spectroscopy (FTIR) was performed using a spectrometer from XXX.

Finally, the particle size distribution of the solids used was determined by laser granulometry. Smaller and more irregular particles tend to have a higher specific surface area and, therefore, greater reactivity in contact with the alkaline source, which can directly influence the mechanical performance and rheological properties of the geopolymeric mortars.

## 3.4 Production of Geopolymeric Mortars and Pastes

### 3.4.1 Mix Design

The development of single-component geopolymeric mortars followed a systematic experimental design, aiming to evaluate the effect of different compositions on physicochemical and mechanical properties.

The variables considered in the study were:

- Proportion between solid precursors (metakaolin and silica fume);
- Content of alkaline activators ( $K_2CO_3$  and  $Ca(OH)_2$ );
- Water/solids ratio (w/s);
- Sand/binder ratio (s/b).

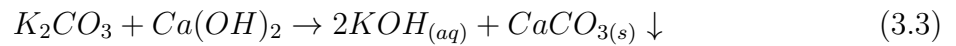
The variable of interest in this experiment is the  $Si/Al$  ratio, which will be varied from 1.0 to 5.0, calculated based on the proportion of metakaolin and silica fume.

Initially, the water/solids ratio was determined analogously to [ref xxxx](#), to ensure adequate workability of the pastes.

In addition, due to stoichiometric balance, the  $Al/K$  ratio will be constant and equal to 1, according to the empirical formula 3.2 (DAVIDOVITS, 1991), where  $M$  is a sodium or potassium cation.

$$M_n \{(SiO_2)_z AlO_2\}_n \cdot wH_2O \quad (3.2)$$

Furthermore, the  $K/Ca$  ratio will be constant and equal to 2, respecting the precipitation reaction of potassium carbonate with calcium hydroxide, as shown in Equation 3.3.



With the paste proportions well defined, the production of mortars maintained a 1:3 ratio between binder and sand, as recommended in the literature [ref XXXX](#).

Table 3.4 presents the different formulations produced, with the respective mass proportions of the components.

TABLE 3.4 – Compositions of the produced geopolymeric mortars.

Sample	Precursors (%)		Activators (%)		w/s	s/b	Si/Al
	MK	SF	$K_2CO_3$	$Ca(OH)_2$			
A1	XX	XX	X,X	X,X	X,XX	X,X	1,0
A2	XX	XX	X,X	X,X	X,XX	X,X	2,0
A3	XX	XX	X,X	X,X	X,XX	X,X	3,0
A4	XX	XX	X,X	X,X	X,XX	X,X	4,0
A5	XX	XX	X,X	X,X	X,XX	X,X	5,0

### 3.4.2 Mixing Procedure

The production of the mixtures followed standardized procedures. For the production of mortars and compressive strength testing, the procedures of the Brazilian standard (Associação Brasileira de Normas Técnicas, 2019) were followed. For the production of pastes, the American standard (ASTM International, 2006) was chosen, since the Brazilian standard does not specify the mixing procedure for cementitious pastes without fine aggregate. Both procedures were adapted for the preparation of small-volume samples.

### 3.4.3 Molding and Curing of Specimens

For the compressive strength test, the specimens were prepared in prismatic molds with dimensions  $XX \times XX \times XX$  mm, previously lubricated with oil-based release agent.

For each composition, 9 specimens were molded, intended for testing at ages of 1, 3, and 7 days (3 specimens for each age). It was not necessary to perform tests at 28 days, as the thermal curing of the binders used provides high initial strength gain, as demonstrated in the literature ref XXX.

Thermal curing was carried out in an oven maintained at  $(60 \pm 2)^\circ\text{C}$  and a minimum relative humidity of 95% for 24 hours, as recommended by the standard (Associação Brasileira de Normas Técnicas (ABNT), 2006), to ensure the activation of the binders and accelerate the curing process. It is noteworthy that demolding was performed 24 hours after the start of the curing process.

Demolding was performed 24 hours after molding, and the specimens were immediately transferred to the corresponding curing conditions until the testing age.

For microstructural analyses, small samples were separated, with hydration interrupted by immersion in ethyl alcohol and vacuum filtration, followed by drying in an oven at  $40^\circ\text{C}$  for 24 hours. These samples were stored in hermetically sealed containers to prevent rehydration.

## 3.5 Characterization of Geopolymeric Mixtures

### 3.5.1 Hardened State Tests

#### 3.5.1.1 Compressive Strength

For the compressive strength test, the specimens were placed in a hydraulic press from XXX, model XXX, applying load at a rate of XXX N/s until failure. The strength was

calculated by the equation:

$$R_c = \frac{F_c}{A_t} \quad (3.4)$$

Where:

- $R_c$  is the compressive strength, in MPa;
- $F_c$  is the maximum applied load, in N;
- $A_t$  is the cross-sectional area, in mm<sup>2</sup>.

For statistical analysis, the Tukey test was performed, allowing the identification of significant differences between sample groups, considering a significance level of XXX%.

### 3.5.2 Microstructural Analyses

#### 3.5.2.1 X-ray Diffraction (XRD)

X-ray diffraction analyses were performed on ground paste samples with particle size less than 75 µm, at ages of 7 and 28 days. A diffractometer from XXX, model XXX, was used.

#### 3.5.2.2 Fourier Transform Infrared Spectroscopy (FTIR)

Infrared spectroscopy was performed on ground paste samples with particle size less than 45 µm, at ages of 1, 3, and 7 days. A spectrometer from XXX, model XXX, was used, in the range of XXX to XXX cm<sup>-1</sup>, with a resolution of XXX cm<sup>-1</sup> and XXX scans.

#### 3.5.2.3 Scanning Electron Microscopy (SEM)

The microstructural analysis of the pastes was performed by scanning electron microscopy, using a microscope from XXX, model XXX, coupled to an energy-dispersive X-ray spectrometer (EDS). The samples were prepared from cylindrical fragments of pastes molded in a disposable plastic straw.

## 4 Results and Discussion

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## 5 Conclusion

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# Bibliography

ANDREW, R. M. Global co 2 emissions from cement production. **Earth System Science Data**, Copernicus GmbH, v. 10, n. 1, p. 195–217, 2018.

Associação Brasileira de Normas Técnicas. **ABNT NBR 7215: Cimento Portland — Determinação da resistência à compressão de corpos de prova cilíndricos**. Rio de Janeiro, Brasil, 2019. Segunda edição. Publicada em 28/02/2019.

Associação Brasileira de Normas Técnicas (ABNT). **ABNT NBR 9479:2006 - Argamassa e concreto — Câmaras úmidas e tanques para cura de corpos-de-prova**. 2. ed. Rio de Janeiro, Brasil, maio 2006. Válida a partir de 30 de junho de 2006.

ASTM International. **ASTM C305: Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency**. West Conshohocken, PA, USA, 2006. Designação oficial: ASTM C305-06.

AWOYERA, A. A. P. O. A critical review on application of alkali activated slag as a sustainable composite binder. **Miscellaneous**, v. 11, p. e00268–e00268, 2019.

BERNAL, S. A.; GUTIÉRREZ, R. M. de; PROVIS, J. L. Engineering and durability properties of alkali-activated slag concretes. **Construction and Building Materials**, Elsevier, v. 33, p. 99–108, 2014.

DAVIDOVITS, J. Geopolymers: Inorganic polymeric new materials. **Journal of Thermal Analysis and Calorimetry**, v. 37, p. 1633–1656, 08 1991.

DUXSON A. FERNÁNDEZ-JIMÉNEZ, J. L. P. P. Geopolymer technology: the current state of the art. **EBSCOhost Academic Search Premier**, v. 42, n. 9, p. 2917–2933, 2006.

GIERGICZNY, Z. Fly ash and slag. **Cement and Concrete Research**, v. 124, p. 105826, 2019. ISSN 0008-8846.

HEATH, A.; PAINE, K.; MCMANUS, M. Minimising the global warming potential of clay based geopolymers. **Journal of Cleaner Production**, v. 78, p. 75–83, 2014.

IEA; WBCSD. **Cement Technology Roadmap 2009: Carbon Emissions Reductions up to 2050**. Paris, France and Geneva, Switzerland, 2009.

KE, X.; BERNAL, S. A.; PROVIS, J. L. One-part alkali-activated materials: State-of-the-art and perspectives. **Cement and Concrete Research**, Elsevier, v. 140, p. 106336, 2021.

- LUUKKINEN Z. ABDOLLAHNEJAD, J. Y. T. One-part alkali-activated materials: A review. **Elsevier ScienceDirect Journals**, v. 103, p. 21–34, 2017.
- MASON, B. Principles of geochemistry. **Miscellaneous**, v. 74, n. 3, p. 262, 1952.
- MORAES, J.; MORAES, M.; BATISTA, J.; AKASAKI, J.; FONT, A.; TASHIMA, M.; SORIANO, L.; BORRACHERO, M.; PAYÁ, J. Influence of sugar cane straw ash in metakaolin-based geopolymers. **Construction and Building Materials**, v. 444, p. 137835, 2024.
- NODEHI, M.; TAGHVAEE, V. M. Alkali-activated materials and geopolymer: a review of common precursors and activators addressing circular economy. **Circular Economy and Sustainability**, v. 2, p. 165–196, 2022.
- PACHECO-TORGAL, F.; LABRINCHA, J.; LEONELLI, C.; PALOMO, A.; CHINDAPRASIRT, P. (Ed.). **Handbook of Alkali-Activated Cements, Mortars and Concretes**. Oxford, UK: Elsevier, 2014. ISBN 9781782422884.
- POLÍTICA Nacional de Resíduos Sólidos: Lei nº 12.305, de 2 de agosto de 2010, e legislação correlata. 3. ed. Brasília: Câmara dos Deputados, Edições Câmara, 2016. (Série Legislação, n. 230). ISBN 978-85-402-0496-6.
- PROVIS, J. L. Alkali-activated materials. **Nature Reviews Materials**, Nature Publishing Group, v. 3, n. 6, p. 276–277, 2018.
- PROVIS, J. L.; BERNAL, S. A. Geopolymers and related alkali-activated materials. **Annual Review of Materials Research**, Annual Reviews, v. 44, p. 299–327, 2014.
- PROVIS, J. L.; DEVENTER, J. S. J. van (Ed.). **Geopolymers: Structure, Processing, Properties and Industrial Applications**. Cambridge, UK: Woodhead Publishing / CRC Press, 2009. ISBN 9781845694494.
- PROVIS, J. v. D. J. L. Geopolymerisation kinetics. 1. in situ energy-dispersive x-ray diffractometry. **Elsevier ScienceDirect Journals**, v. 62, n. 9, p. 2309–2317, 2007.
- QIN, Y.; QU, C.; MA, C.; ZHOU, L. One-part alkali-activated materials: State of the art and perspectives. **Polymers**, v. 14, n. 22, p. 5046, 2022.
- RAJAN, P. K. H. S. Sustainable development of geopolymer binder using sodium silicate synthesized from agricultural waste. **Elsevier ScienceDirect Journals**, v. 286, p. 124959–124959, 2020.
- RAKHIMOVA, N. R.; RAKHIMOV, R. Z. Reaction products, structure and properties of alkali-activated metakaolin cements incorporated with supplementary materials – a review. **Journal of Materials Research and Technology**, v. 8, n. 1, p. 1522–1531, 2019.
- SCRIVENER, K. L.; JOHN, V. M.; GARTNER, E. M. Eco-efficient cements: Potential economically viable solutions for a low-co2 cement-based materials industry. **Cement and concrete Research**, Elsevier, v. 114, p. 2–26, 2018.
- SEVERO, C. G. S.; COSTA, D. L.; BEZERRA, I. M. T.; MENEZES, R. R.; NEVES, G. A. Características, particularidades e princípios científicos dos materiais ativados alcalinamente. **Revista Eletrônica de Materiais e Processos**, v. 8, n. 2, p. 55–67, 2013.
- United Nations. **World population prospects: The 1994 revision**. [S.l.]: UN, 1995.

# Appendix A - Tópicos de Dilema Linear

## A.1 A First Section for the Appendix

The Linear Dilemma matrix  $M$  and the inertial torque vector  $b$ , used in the simulation, are calculated according to the formulation below:

$$M = \begin{bmatrix} M_{11} & M_{12} & M_{13} \\ M_{21} & M_{22} & M_{23} \\ M_{31} & M_{32} & M_{33} \end{bmatrix} \quad (\text{A.1})$$

# Annex A - Exemplo de um Primeiro Anexo

## A.1 Annex A: Example of Annex

Example of a table.

TABLE A.1 – Example of a Table

Parameter	Unit	Simulation value	Experimental value
Length, $\alpha$	$m$	8.23	8.54
Height, $\beta$	$m$	29.1	28.3
Velocity, $v$	$m/s$	60.2	67.3

Example of an equation

$$\frac{d}{dt}(\frac{\partial L}{\partial \dot{q}}) - \frac{\partial L}{\partial q} = \tau^T. \tag{A.1}$$

## FOLHA DE REGISTRO DO DOCUMENTO

1. CLASSIFICAÇÃO/TIPO TC	2. DATA 26 de maio de 2025	3. DOCUMENTO Nº DCTA/ITA/DM-018/2025	4. Nº DE PÁGINAS 35
5. TÍTULO E SUBTÍTULO: Desenvolvimento de cimento ativado alcalinamente monocomponente com precursores sólidos de baixo teor de cálcio e fontes alcalinas alternativas.			
6. AUTOR(ES): <b>Felipe Mello dos Reis</b>			
7. INSTITUIÇÃO(ÕES)/ÓRGÃO(S) INTERNO(S)/DIVISÃO(ÕES): Instituto Tecnológico de Aeronáutica – ITA			
8. PALAVRAS-CHAVE SUGERIDAS PELO AUTOR: Cupim; Cimento; Estruturas			
9. PALAVRAS-CHAVE RESULTANTES DE INDEXAÇÃO: Cupim; Dilema; Construção			
10. APRESENTAÇÃO: (X) Nacional ( ) Internacional ITA, São José dos Campos. Curso de Graduação. Programa de Graduação em Engenharia Civil-Aeronáutica. Departamento de Estruturas e Edificações. Orientador: Prof. Dr. João Cláudio Bassan de Moraes . Coorientadora: Pamela Rodrigues Passos Severino. Defesa em 26/05/2025. Publicada em 26/05/2025.			
11. RESUMO: <p>In the search for more sustainable alternatives to Portland cement, alkali-activated cements have been extensively studied. However, most mixing processes occur in two separate steps, limiting their feasibility and constructive efficiency. A significant advancement in this field is the development of one-part (just-add-water) systems, which simplify production and make the technology more accessible and practical. Nonetheless, current studies mainly focus on calcium-rich precursors, while the use of conventional alkaline activators raises concerns related to safety and cost. This work proposes the development of a one-part alkali-activated cement using low-calcium solid precursors, such as silica fume and metakaolin, along with safer and more affordable alkaline sources, such as potassium carbonate and calcium hydroxide. The goal is to ensure adequate mechanical performance while enhancing the viability of these materials for application in the construction industry.</p>			
12. GRAU DE SIGILO: (X) OSTENSIVO ( ) RESERVADO ( ) SECRETO			