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Research Article

Evaluation of a Sustainable Geopolymer Mortar as an Alternative to Portland Cement Mortar in Civil Construction

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Abstract

Geopolymer is an alkaline activating material composed of aluminosilicates with interesting physical and chemical properties, it can be a more sustainable alternative to cements. Based on a methodology adapted from the ABNT NBR 16,738 standard, 3 parts of sand and variable parts of water were mixed with metakaolin and 1:5 weight ratio of powder activator (sodium hydroxide to sodium silicate). In the exploratory tests, for 3 days of curing, 18.5 MPa was obtained for the geopolymer mortar with 0.55 parts of water and binder with SiO_2/Al_2O_3 ratio of 3.78. For Portland cement mortars, compressive strength varied from 4 to 7 MPa using 0.50 parts of water and 4 to 5 MPa using 0.55 parts of water. In the tests, for 28 days of curing, the geopolymer mortar with 0.50 parts of water reached about 19 MPa and the Portland cement mortar 13 MPa. Although the specific cost of the sustainable alternative mortar is 37% higher than the traditional Portland cement one, the reduction in CO_2 emissions and the increased compressive strength are significant.

Keywords: Geopolymer Mortar; Portland Cement; Metakaolin; Sustainability

Introduction

Civil construction is a key area for the economic development of a country. Considering the post-pandemic period, investments in infrastructure are expected to grow, which leads to increase cement consumption. Only in the years of 2019 and 2020, it was estimated that the production of cement was responsible for emitting about 540 kg of CO_2 per ton (PENNA, 2020) [1] which corresponds to 2.6% of total greenhouse gas emissions in Brazil. Thus, it is important to study more sustainable alternatives to this material, in order to meet the global demands for reduction of greenhouse gases, as highlighted in the 2030 Agenda of the United Nations [2]. According to the National Cement Industry Union (SNIC), 38.6 million tons of cement were sold in the first eight months of 2020, representing an increase of 7.5% over the same period in 2019 [3]. Given the large consumption of Portland cement in Brazil and its high polluting potential, geopolymer binder is presented as a more ecological solution. Geopolymer is an alkaline activating material composed of aluminosilicates that has high resistance to compression, to acid and sulfate attack and to high temperatures, as well as lower CO_2 emissions than Portland cement. Some essential control parameters for its production are the mineralogical composition of the precursor material (aluminosilicates, such as metakaolin, fly ash and granulated blast furnace slag), the concentration of activating reagents, the amount of water and the curing time (Azevedo, Zhang et al. [4]).

Background

According to the Brazilian Association of Portland Cement – ABCP (2021), cement is a thin material with binding properties that hardens when in contact with water which cannot be decomposed with a subsequent possible interaction with water [5]. It is mainly composed of clinker (a mixture of limestone, clay and chemical components) and other substances that give it different properties, such as gypsum (longer setting time), slag (greater durability in the presence of sulfate) and clay (greater impermeability to concrete and limestone, resulting in a lower cost). Although all types of cements are suitable for different applications, some are more advantageous than others depending on the situation. Portland CP-II cement is a versatile material and applies to all kinds of civil works

(PUGLIESI, 2018) [6], and it is characterized by less heat released in contact with water and compressive strengths from 25 to 40 MPa with 28 days of cure. In Brazil, it is regulated by the Brazilian Association of Technical Standards - ABNT NBR 11,578 [7] and is composed of a mixture with other materials, namely: CP-II E (blast furnace slag), CP-II Z (pozzolanic material) and CP-II F (carbonatic material as a filler).

According to Nergis, Abdullah, Vizureanu and Tahir (2018), the industrial use of the reaction of kaolinite (mineralogical term that describes the hydrated aluminum disilicate, Al2SiO5(OH)4, which is the main constituent of kaolin in about 40–70%) with alkaline activators dates to 1934 in the ceramic industry [8]. Equation (1) shows how this reaction takes place:

$$(Si_2O_5, Al_2(OH)_4 + NaOH) \xrightarrow{\Delta 100\text{-}150°C} Na(\text{-}Si\text{-}O\text{-}Al\text{-}O)_n \quad (1)$$

Kaolinite Hydrosodalite

These authors also mention that this reaction can lead to a compressive strength of approximately 12 MPa and a porosity of 40% [8]. This is a positive feature due to the predictability regarding mechanical and physical performances of geopolymers using metakaolin.

For Santos (2017), the SiO_2/Al_2O_3 molar ratio greatly affects geopolymerization, as the SiO_2 concentration has a direct impact on the formation of Si-O-Al polymeric networks. Consequently, the Si/Al ratio is also important in the study of geopolymers. The increase in the molar ratio causes an increase in the geopolymers setting time, which may be related to the decrease of Na_2O in the system and the slower dissolution of the silicate species compared to the aluminum dissolution [9].

Vassalo (2013) showed that the curing process and the molar content of the activator were essential for the physical, chemical and structural development of geopolymers. Geopolymers were obtained by activating metakaolin with sodium hydroxide (in different molarities) at room temperature and in an oven at 85±3°C. It was observed that temperature interfered in the initial strengths (greater for the samples cured in the oven), although the molar content of the activator and the composition of the oxides were probably the main factors responsible for the final strengths obtained (greater in lower molarities of activator - about 11.5 MPa - with a negligible variation between room temperature and oven) [10].

This study strives to compare Portland cement mortar with geopolymer mortar obtained from alkaline activation with metakaolin, a highly reactive amorphous material suitable for cementitious applications (NERGIS, 2018 apud RASHAD, 2013) which can be obtained by calcining kaolin in temperature around 750 °C for 2 hours (PETERMANN, SAEED e HAMMOND, 2012 apud PUERTAS, MARTINEZ-RAMIREZ, ALONSO e VAZQUEZ, 2000) [8, 11].

Methodology

The methodology in this paper was based on the ABNT NBR 16,738 standard for determining the compressive strength of prismatic Portland cement specimens [12]. The materials were commercial sand, commercial cement, water, metakaolin, sodium silicate, sodium hydroxide, metal mold with dimensions 40 x 40 x 40 mm, planetary mixer and vibrating table.

The tests performed with commercial cement were carried out as explained below, using a planetary mixer:

1. All the water has been put in.
2. Gradually, all the cement was added, turning the mixer on at low speed for 30 seconds.
3. The commercial sand was added, and, at the end, the mixer was turned on for another 30 seconds at high speed.
4. The mixture was left to rest for 90 seconds, the first 30 being used to remove material from the walls and the last 60 to complete rest.
5. The mortar was mixed for another 60 seconds at high speed.
6. The specimens were molded on a vibrating table, adding the material in portions and distributing the material evenly.

In the first 24 hours, the specimens were kept in the mold. Until the moment of the compressive strength test, the samples were submitted to room temperature, around 23±2°C, in a dry condition.

Exploratory Tests

Initially, 3 exploratory tests were carried out with compressive strength tests at 3 days of cure: test 1 using Portland cement with 0.5 parts of water; test 2 using geopolymer binder with 0.55 parts of water and test 3 using Portland cement with 0.55 parts of water. 7 samples were produced for each test considering the amounts of material in Table 1.

Table 1: Amount of material in the production of mortar.

Test	Cement/Binder	Sand	Water	Total
1	1	3	0.5	4.5
2	1	3	0.55	4.50*
3	1	3	0.55	4.50*

*The proportions of materials were based on 4.50 parts of mortar, even though 0.05 parts of water was added later for more workability.

In Table 2, MK refers to metakaolin, SS to sodium silicate and SH to sodium hydroxide.

Table 2: Amount of material in the production of geopolymer binder.

Binder	MK	SS	SH	Subtotal
Part	0.7	0.25	0.05	1

Tests

Tests 4 were also carried out using Portland cement and 5 using geopolymer binder, reproducing the proportions of materials from test 1 (standard of ABNT NBR 16,738 [12]) in Table 1 and of binder in Table 2. In total, 3 specimens were produced for each one of both compressive strength tests at 1, 3, 7, 14 and 28 days of cure.

Compressive strength tests were performed with continuous application of force, without shock, at a loading speed of, approximately, 2400±200 N/s.

Sand particle size distribution was determined by dry sieving in 20cm diameter sieves, and metakaolin particle size distribution was determined by laser particle sizer.

Finally, the mineralogical composition of metakaolin was determined by X-ray diffraction (XRD) and the chemical composition by X-ray fluorescence (XRF).

Results And Discussions

Material Characterization

The commercial sand used in tests 4 and 5 was classified and distributed in the proportions described in Table 3, according to the average values of accumulated pass-through percentage of the ISO standard sand. As for the exploratory tests 1 to 3, no classification procedures were performed (Table 3).

Table 3: Particle size distribution of ISO standard sand.

Standard Particle Size	Practical Particle Size	Minimum	Average	Maximum
mm		% Cumulative Passing		
2	2.36	100	100	100
1.6	1.7	88	93	98
1	0.84	62	67	72
0.5	0.6	28	33	38
0.16	0.15	8	13	18
0.08	0.08	0	1	2

Table 4 shows the particle size distribution of metakaolin, in which particles finer than sand are identified.

Table 4: Particle size distribution of metakaolin.

Material	D10 (µm)	D50 (µm)	D90 (µm)
MK	12.1	22.4	38.8

The results obtained for the XRF test are shown in Table 5.

Table 5: Composition of materials used in the binder of test 2.

Material	Proportion (%)	SiO_2 (%)	Al_2O_3 (%)	Na_2O (%)	K_2O (%)
MK	70	60	32.2	0.1	1.8
SS	25	32.6	-	14.6	-
SH	5	-	-	77.5	-
Total (%)	100	50.2	22.5	7.6	1.3

The total of each one of the mineral species in the binder shown in Table 5 was calculated based on equation 2:

$$\text{Total (\%)} = \frac{\sum(\%\textit{Proportion of material in the binder} \times \%\textit{ respective percentage of mineral species})}{100} \quad (2)$$

Considering the molar masses of Al2O3 (101.96 g/cm^3) and SiO2 (60.08 g/cm^3), the Si/Al ratio is equal to 3.9 for the binder in test 2 and the of SiO2/Al2O3 is equal to 3.78. Many authors show that the ideal SiO2/Al2O3 molar ratios are in the range of 3.0 to 5.5 to immobilize contaminants in geopolymers (Santos Apud Davidovits et al.), [9,10]. Thus, test 2 presents silica and aluminum concentrations consistent with the literature.

Furthermore, according to the XRD test, metakaolin is composed of muscovite, kaolinite, quartz, hematite and amorphous phases. The commercial Portland cement is composed of calcium sulfate, calcium silicates, iron, aluminum and limestone (filler), as given by the manufacturer.

Compressive Strength Tests

Exploratory tests

Figure 1 shows the results of compressive strength tests carried out in 3 days of cure. Test 2 got the highest result of compressive strength with 3 days of cure, which may be related to its SiO2/Al2O3 lower ratio, as the higher this ratio, the longer the geopolymers set time (reaction delay), according to Santos (2017) [9].

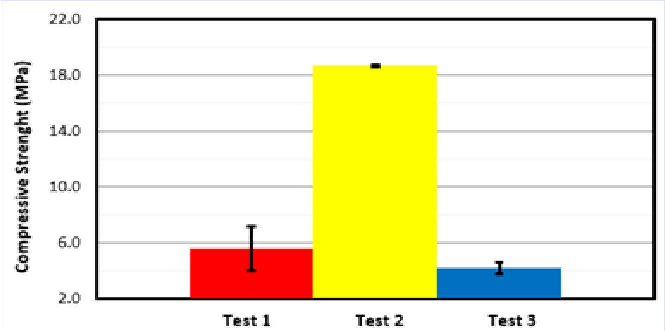

Figure 1: Compressive strength results in 3 days of curing.

The compressive strength results of tests 1 and 3 were similar, although the first one comes closer to the standard established by ABNT NBR 11,578 for Composite Portland Cement, in which the mortar must have a compressive strength equal to or greater than 8 MPa after 3 days of cure [7]. Thus, it is demonstrated that the closer the mass of water added to the proportion used in the ABNT NBR 16,738 standard for determining the compressive strength of prismatic Portland Cement specimens, the greater the compressive strength of the mortar with Portland cement. In other words, the greater the amount of water, the worse the compressive strength for this material.

Test 2, on the other hand, proved to be quite satisfactory using the methodology in this study. It is observed that a greater amount of water in the geopolymer mortar with the same proportion of materials used in Portland cement (ABNT NBR 16,738) is conducive to increasing the compressive strength [12]. Furthermore, it is noticed that a ratio of 1: 5 SH:SS gives adequate results.

Tests

Tests 4 and 5 were performed respectively for Portland cement and geopolymer mortars using the methodology and material proportions of the ABNT NBR 16,738 standard [12]. For the compressive strength tests, the amounts of mortar components described in Table 1 and those of binder in Table 2 were reproduced. The results are shown in Figure 2, in comparison with the expected compressive strength values by the ABNT NBR 11,578 standard for Composite Portland cement (Figure 2).

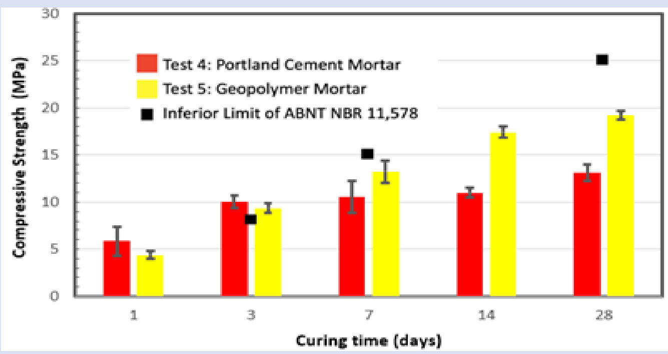

Figure 2: Compressive strength results over time compared with the ABNT 11,578 standard for Composite Portland Cement.

The compressive strength of the tests followed the tendency to increase over time. On one hand, the development of Portland cement mortar was faster in the first days and stagnated after 7 days of age. Differently from the standard ABNT NBR 16,738, in which the samples are kept submerged in water [12], in this study they were cured in a dry situation. This may indicate the low development in later ages, as the direct contact with air can dry the material and make it more brittle.

On the other hand, the development of the geopolymer mortar was lower on the first day of curing. According to Vassalo (2013) apud Diaz et al. (2011), a higher curing temperature can lead to higher initial results, as the dissolution of metakaolin would be more intense and the condensation of the reaction products more homogeneous due to less water retention within the microstructure [10]. Compared to ABNT NBR 11,578, the geopolymer mortar compressive strength after 3 days of cure is lower than the minimum required and after 7 days is within a reasonable range. This finding is close to the view of Ramesh and Srikanth (2020), who said that geopolymer mortar can be cured at both high temperatures and at room temperature [13].

In 28 days of age, 19 MPa were obtained for geopolymer mortar and 13 MPa for Portland cement mortar. In comparison with the inferior limit of the ABNT NBR 11,578 standard (25 MPa) [7], tests 4 and 5 are not suitable for industrial application. Therefore, the methodology used in this study must be rethought: a geopolymer mortar test with a greater amount of water is indicated, as done in tests 2 and 3, as shown in Table 1, and a Portland cement mortar test whose cure is made with the bodies submerged in water. In addition, further studies regarding the proportion of activators in the binder can be re-evaluated, as Vassalo (2013) believes that the molar content of activators, together with the composition of the oxide content used in the geopolymer reaction, are the main agents responsible for the final compressive strengths [10].

Economic Evaluation

In view of the great compressive strength result obtained in test 2 and shown in Figure 1, the geopolymer mortars can be considered as more sustainable alternatives to Portland cement ones, as they produce lower CO2 emissions and have interesting characteristics for civil construction, such as high resistance to high temperatures and resistance to acid corrosion. For this reason, Table 6 presents an economic comparison between these materials.

Table 6: Economic comparison of mortars.

Materials	Components	Price (BRL/kg)	Parts	Mass (g)	Cost (BRL/kg)	Investment (BRL/kg)
Portland Cement Mortar	Cement	0.45	1	225	0.1	0.13
	Sand	0.05	3	675	0.03	
	Water	0.002	0.5	112.5	0.0002	
Geopolymer Mortar	Binder	1.18	1	225	0.27	0.3
	Sand	0.05	3	675	0.03	
	Water	0.002	0.5	112.5	0.0002	
Binder Materials	MK	0.58	0.7	157.5	0.09	1.18
	SH	2.45	0.24	56.3	0.14	
	SS	3.15	0.06	11.3	0.04	

Based on Table 6, the geopolymer mortar presents an investment 2.3 times greater than the Portland cement one, as the cost per kilogram of binder is still much higher than the other components. However, it is noteworthy that the prices of reagents for a higher production (in the order of tons) is generally lower and its more frequent use by industry can also reduce these values.

Although there is a higher investment cost for the production of geopolymer mortar, it is necessary to consider the associated social and environmental gains. In 2017, Assi et al. [14] achieved a 40% reduction in CO2 emissions compared to Portland cement mortar. In 2020, the same authors apud McLellan et al. (2011) noted a 7-39% increase in the cost of geopolymer at the expense of a 44-64% reduction in greenhouse gas emissions [15].

According to the website Geopolymer - Geo-Pol (2021), geopolymer mortars produces up to 6 times less CO2 than Portland cement mortars, as well as have advantageous physicochemical properties, such as relatively high compressive strength in a few hours, low thermal conductivity, ability to immobilize heavy metals, resistance to high temperatures, chemical attack and immunity to alkali-silica reaction. Moreover, the raw material of a geopolymer binder can be any inorganic material composed of amorphous silica and alumina (more reactive) [16].

Thus, even though more costly, the use of geopolymer mortar not only enables a paradigm shift in relation to the sustainability of the civil construction industry processes, but also opens doors to the use of siliceous materials that are often not used economically, such as iron ore tailings. Guimarães et al. [17] and Borges et al. [18] obtained satisfactory results in the application of iron ore tailings in the production of mortar and concrete.

Conclusion

For the exploratory tests using Portland cement, test 1 and test 3 obtained compressive strength results between 4 and 7 MPa using 0.50 parts of water and 4 to 5 MPa using 0.55 parts of water after three days of cure, respectively. This shows that the first one came closer to the inferior limit of the ABNT NBR 11,578 standard, which establishes 8 MPa for bodies in this age. Therefore, for this study, the greater the amount of water added to the Portland cement mortar, the lower the compressive strength.

For the exploratory tests using geopolymer binder, test 2 obtained compressive strength result around 18.5 MPa after three days of cure. This contributes to the fact that the binder in this study has an adequate SiO2/Al2O3 ratio with the literature, characterized by a low setting time. Also, for this methodology, the 1:5 SH:SS ratio and the addition of a larger amount of water (compared to Portland cement mortar) work well.

For the tests, there is a trend to increase the compressive strength over time. Although the development of Portland cement mortar is accelerated in the first days, it stagnates after 7 days of age, which may be related to the dry curing in direct contact with air of the samples. As for the geopolymer mortar, the first day of curing had a lower result than the one with Portland cement, which may be associated with a milder curing temperature, which is related to greater water retention and, consequently, lesser dissolution of metakaolin and less homogenization of condensation of reaction products. Even so, the compressive strength after 3 days of cure is above the minimum required and after 7 days it is within a reasonable range. However, the 28-day-old results for both tests with Portland cement mortar and geopolymer mortar do not fit the inferior limit of the ABNT NBR 11,578 standard. For this reason, further studies and different approaches are recommended, such as adding more water to the geopolymer mortar, submerging the Portland cement mortar bodies in water during curing and reassessing the proportion of activators in the geopolymer binder.

Finally, one of the main advantages in the use of geopolymer mortars are the reduction in the emission of greenhouse gases and greater compressive strengths. Thus, even though the economic evaluation showed that a sustainable mortar is 2.3 times more costly than Portland cement mortar, the paradigm shift in relation to the sustainability of civil construction industry processes is considerable, and still allows doors to be open to the use of siliceous materials that are often not used economically, such as iron ore tailings.

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