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Evaluation of thermal and mechanical behavior of pavers with waste additions

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Abstract

New materials and technologies used in construction constantly need improvements, whereby the leveraging of new raw materials for the manufacture of products already in use, such as paving, is required. Thus, this study aimed to determine the mechanical and thermal behavior of pavers containing waste glass and São Tomé stone waste to verify their potential application as cold diffraction. Thereafter, they were comminuted and added to the mixtures for making the pavers having glass waste and São Tomé stone in the range of 0–30% by weight. Mechanical compressive strength and thermal heat absorption tests were performed. Results showed that the replacement of fine aggregates with waste glass and São Tomé stone waste in pavers reached a mechanical resistance of approximately 85% and 73% of that of the reference paver, respectively. The results show that reducing the waste content of pavers can increase the mechanical strength to reach the NBR 9781/87 values. However, pavers with lower mechanical strength can be used in paving pedestrian sidewalks, where the loads are low. Pavers with 30% glass waste achieved a 5.5% reduction in the maximum temperature, which could contribute to the reduction of urban heat islands.

Keywords: pavers, cold materials, glass waste, stone São Tomé.

1. Introduction

The effect known as heat island is due to the high temperature that is associated with changes in radiation and thermal properties linked to various urban activities. The heat from solar radiation depends on the structure of the city. It is estimated that cities occupy 2% of the Earth's surface, and their inhabitants consume 75% of the energy resources of the world. However, some strategies can mitigate these heat island effects, such as the inclusion of vegetation, the type of pavement surfaces, the albedo, and types of materials used in construction (Gago *et al*., 2013).

Therefore, thermal modification in the urban environment alters the energy balance, generating socioeconomic problems and increasing energy consumption (Kim & Brown, 2021). In recent decades, there have been concerns regarding the environment and production of new materials. Increasingly more sustainability measures are sought in the economic, social, and environmental spheres through alternative measures, such as evaluating the partial replacement of aggregates in concrete, as well as waste reuse (Machado *et al*., 2022).

The increasing use of glass materials in everyday life is notable. Even though this is a 100% recyclable material, the worldwide recycling rate for glass waste is low. Only 21% of the total amount of glass produced in the world is recycled. The remainder is destined for landfills (Harder, 2018). Therefore, using glass waste in concrete, asphalt, and masonry blocks enables the reuse and recovery of glass waste, reducing the amount of glass that ends in landfills and alleviating environmental problems (Balan *et al*., 2021).

In the context of improving thermal comfort, glass waste can be a good alternative when used on pavements (Guo *et al*., 2020). In addition to glass waste, according to (Queiroz *et al*., 2018), São Tomé stone has interesting characteristics that improve the thermal quality of the environment; when used as coatings, it can contribute to good ambient conditions, and consequently, low energy consumption when using air conditioners. Furthermore, if the thermal characteristic of the material is maintained, the waste generated during its extraction can be used for the development of new materials that can be used in pavements.

Therefore, the objective of this study is to characterize São Tomé stone and glass waste, evaluate their thermal and mechanical behavior in urban pavers, and investigate the feasibility of replacing the raw material (stone dust) with waste. This can help improve the environment by using waste, reducing the number of inputs, and reducing the effect of urban heat islands.

2. Materials and Method

Pozosul CP V-ARI RS cement was used for this study. The fine aggregates used were fine sand, stone dust, a by-product of the automotive industry—laminated glass (Polyvinyl butyral (PVB))—and São Tomé stone. Gravel 0 (granulometry 4.8 to 9.5 mm) was used as the coarse aggregate. All materials were obtained from suppliers located in the south of Santa Catarina State - Brazil.

Glass waste was cut manually with the aid of a grinder and comminuted in a hammer mill, Furlan's model MM Mancheste with 8 mm grids, rotation 1100 - 1200 rpm. Next, sieving was carried out, using a ¼ mesh sieve with a 6.30 mm opening to separate the larger particles of polymeric material. Then, the previously comminuted glass waste was ground again with 2 mm grids. Large São Tomé stones were manually fragmented with the aid of a sledgehammer and introduced into the above-mentioned hammer mill with the same rotation and 8 mm grids. Subsequently, a granulometric analysis of both was performed, following the guidelines of NBR 248:2003, making sure that the dimensions were between the lower and upper limits according to NBR 7211:2009.

To evaluate the thermal behavior of São Tomé stone in samples of pavers, a technique of differential thermal analysis (Netzsch SDT Q 600 equipment, model STA 449F3 Jupiter), with a heating rate of 10 ºC/min from 35 to 1000 ºC, under a nitrogen flow of 60 mL/min, was employed. To determine the elemental chemical composition of each raw material, X-ray fluorescence (FRX) was used with wavelength dispersion in X-ray equipment (Philips brand, model PW 2400). The X-ray diffraction was performed using Rigaku equipment, model Miniflex 300 with CuK α radiation of 1.541862 Å, voltage of 30 kV, and electric current of 10 mA. The samples were read between 20º and 100º (2θ) and a speed of 0.02º/s.

The material was mixed using a vibro-press equipment (model MBP-4, Menegotti), in which the concrete was pressed, vibrated, and compacted in a hydraulic and automated process, which generated 12 units at a time. The dimensions of the pavers were 100 mm x 200 mm x 80 mm. For each sample of pavers, 50 units were produced.

The reference mix consisted of cement, fine sand, pebbles, and stone powder in the ratio of 1:1:0.5:5, respectively, with an optimum humidity of 8%. After the reference mix, mixtures were made with different percentages of glass waste and São Tomé stone waste, $P_{V0,PST30}$, $P_{V30,PST0}$, $P_{V30,PST30}$; $P_{V15,PST15\,(1)}$ and $P_{V15,PST15\,(2)}$ in which nomenclature P refers to paver, V refers to glass waste, PST to São Tomé stone waste, and the numbers in the sequence refer to the amount of stone powder substituted.

Water absorption and void index tests were performed after curing the specimens for 50 days according to the procedures standardized by NBR 9781:2013 and NBR 9778:2009, respectively. Compressive strength tests were performed at 7, 21, and 28 days using the EMIC PC 200 hydraulic press, with a loading speed of 550 kPa/s, as established by NBR 9781:2013.

To measure the thermal behavior of the specimens, three data loggers were used (two Novus Fieldlogger S/IHM, and one by PicoLog) simultaneously, with type-k thermocouples being glued with a thermal paste (Implastec) on the surface of the paver. This test was performed indoors; specimens were randomly dispersed in triplicate and subjected to artificial light radiation from 35 tungsten filament incandescent light bulbs of 100 W each. In the second step, the measurements were performed in an open-air outdoor environment, with the specimens placed in a way that no specimen was under any shadow.

The experimental results were analyzed using the statistical significance of the independent variables, called the replacement of glass waste and São Tomé stone waste on the pavers results. The experimental design was the factorial 2^2+2 two central points. The statistical methods used were ANOVA Pareto and response surface. Combinations of results with p-value $<$ 0.1 were considered significant, which corresponds to a reliability equal to or above 90%. Statistica 7 software, free-trial version, was used for these statistical analyses.

3. Results and Discussion

The results of the chemical analysis carried out on ground samples of São Tomé stone and glass wastes showed 86.09% and 71.90% silicon dioxide (SiO_2) composition, respectively. Table 1 presents the compounds identified in the chemical analysis and their respective amounts

Table 1 - Chemical analysis of São Tomé stone waste and glass waste.

São Tomé stone waste								
Compound Amount (%)	SiO_2	K_2O	Al_2O_3	Fe_2O_3	CaO	P_2O_5	TiO_2	SO_3
	86.09	4.25	3.78	2.41	1.43	1.08	0.47	0.42
glass waste								
Compound Amount (%)	SiO_2	Na_2O	CaO	MgO	Fe_2O_3	Al_2O_3	K_2O	ZnO
	71.90	12.86	8.83	3.97	0.83	0.76	0.24	0.13

Alecrim (2009) mentions that the chemical composition of quartzite has a high silica content (SiO_2), and may contain small amounts of aluminum, iron, and calcium, among other elements in lower amounts. Vita *et al*. (2022) found that the composition of quartzite, known as São Tomé stone, varies according to its color; the gray or dark gray/greenish, yellowish, yellowish gray, grayish brown or pink, and yellowish gray contain 82%, 95%, 57%, 62%, and 61% quartz, respectively. Therefore, as the sample under study started from a waste in which several types of São Tomé stone were present, it is expected that the chemical composition is heterogeneous; that is, not following the pattern of any given type of stone.

For glass waste, the amount of SiO_2 shown in Table 1 exceeds the values obtained from the chemical composition of the laminated glass waste sample used in the study by Souza-Dal Bó *et al*. (2021) in which the glass layers were separated from the PVB and the following amounts were found: 69.2% SiO_2 , 13.3% Na_2O, 9.1% CaO, 3.8% MgO, 1.7% Al_2O_3, 0.4% Fe_2O_3, and 0.2% K_2O.

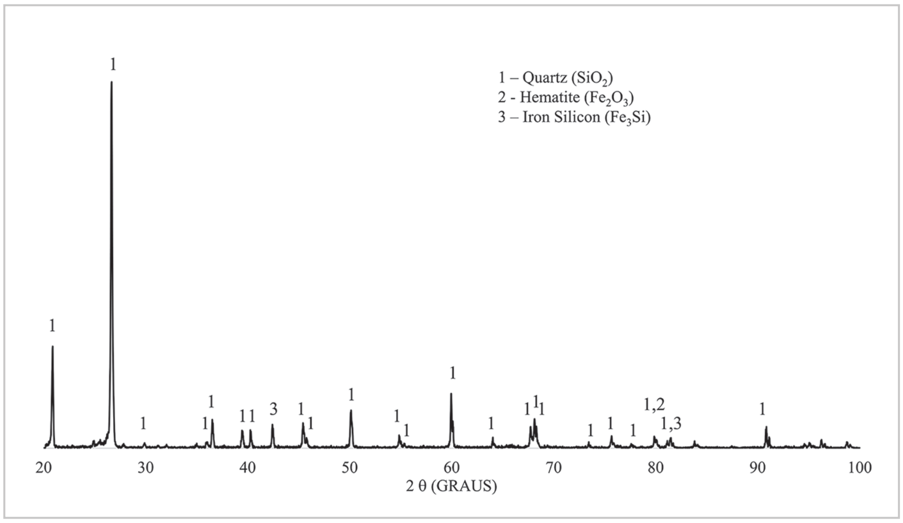

Figure 1 - Diffractogram obtained from the São Tomé stone waste.

Figure 1 quartz (card number 00-083-0539) appears frequently, and is present in greater proportion than other compounds, such as hematite (card number 00-073-0603) and ferro silicon (card number 00 -065-0994). This result is consistent with that found by Tamilarasi *et al*. (2021) that quartz is the main mineral in rock samples. It was confirmed that the glass waste sample was an amorphous material, since there were no peaks. Iglesias *et al*. (2022) state that the amorphous structure of the glass remains unchanged, regardless of the type of glass used.

The results obtained from the granulometric distribution test carried out on fine aggregates (fine sand and stone powder) and coarse aggregates (bite nº 0), on São Tomé stone and glass wastes after the comminution process showed the variation in particle size. Table 2 presents the granulometry results.

Table 2 - Distribution of granulometric composition of São Tomé stone waste.

Description	fineness modulus	Maximum diameter (mm)
Thin sand	3.26	0.6
Grit	2.65	4.75
gravel n°0	3.1	19
São Tomé stone waste	3.03	1.18
Glass waste	2.87	2.00

Table 2 shows that the lowest fineness modulus is for stone powder, followed by glass waste and São Tomé stone waste, being 2.65, 2.87, and 3.03, respectively. Regarding the maximum diameter, gravel nº0 obtained 4.75 mm being the largest compared to the others. Figure 2 presents the distribution of the granulometric composition of aggregates and wastes with their respective fineness limits according to NBR 7211:2009.

Fine sand has a granulometry that goes through all the optimal and usable limits. Both fine sand and the São Tomé stone waste meet the parameters established by the standard, having the fineness modulus of the upper usable zone ranging from 2.9 to 3.5. The stone powder and glass waste were between the optimal and usable zones, also with an adequate granulometry and fineness modulus of the optimum zone that varies from 2.2 to 2.9. These results show that the use of fine sand and stone powder mixed with São Tomé stone and glass waste allowed the same to occupy the empty spaces in the mixture, owing to their smaller size. Such occupation, according to the conclusions of Gleize (2009) increases the mechanical strength of concrete by reducing air voids.

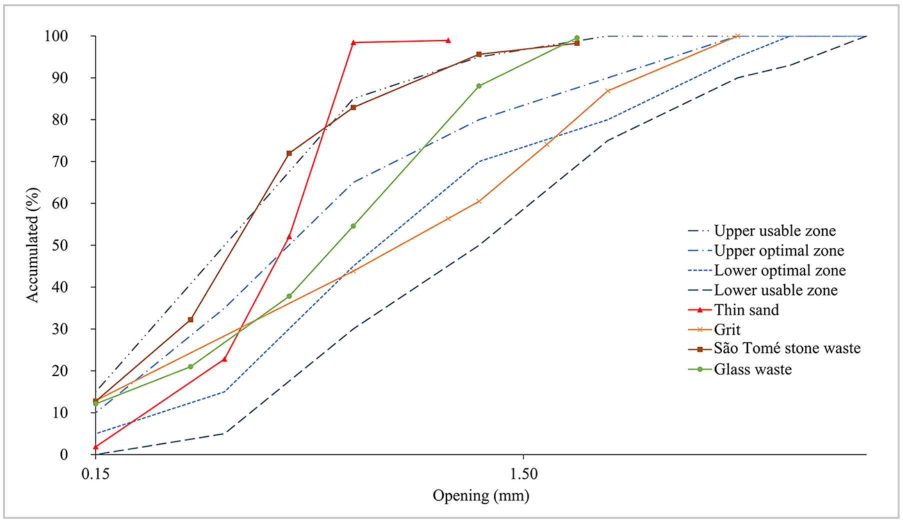

Figure 2 - Distribution of granulometric composition and limits established by the standard.

The result of thermogravimetry with samples of ground pavers shows the loss of material mass with temperature increase. Figure 3 shows that paver P V30, PST0, had the highest loss of concrete mass caused by the thermal decomposition of the polymeric materials in the glass waste. Furthermore, Song *et al.* (2022) mention that the loss of water up to 200 °C may also be due to the dehydration of chemically bound water in hydrated products of calcium silicate and ettringite. In sequence, it is possible to notice that the mass loss curves of the concrete that has a higher content of glass waste has greater mass loss. The paver P V0, PST30 with São Tomé stone waste has the lowest mass loss. The mass loss at 400 °C is related to the decomposition of calcium hydroxide. The mass loss at 600 °C is related to the degradation of CH (Salih *et al.*, 2022). Figure 4 shows the results of water absorption (A) and void index (I_v).

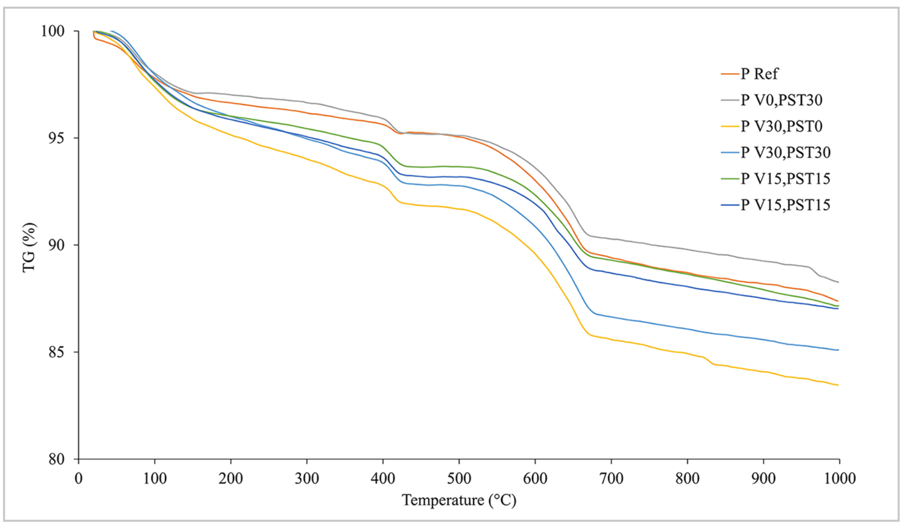

Figure 3 - Thermogravimetry (TG) of ground paver waste.

P V30, PST30 has greater water absorption and void index, as the paver with the highest content of substituted wastes (30% of glass waste and 30% of São Tomé stone waste). The experiment with the composition P V30, PST0 presented the lowest mean values of water absorption (5.84%) and void index (19.50%).

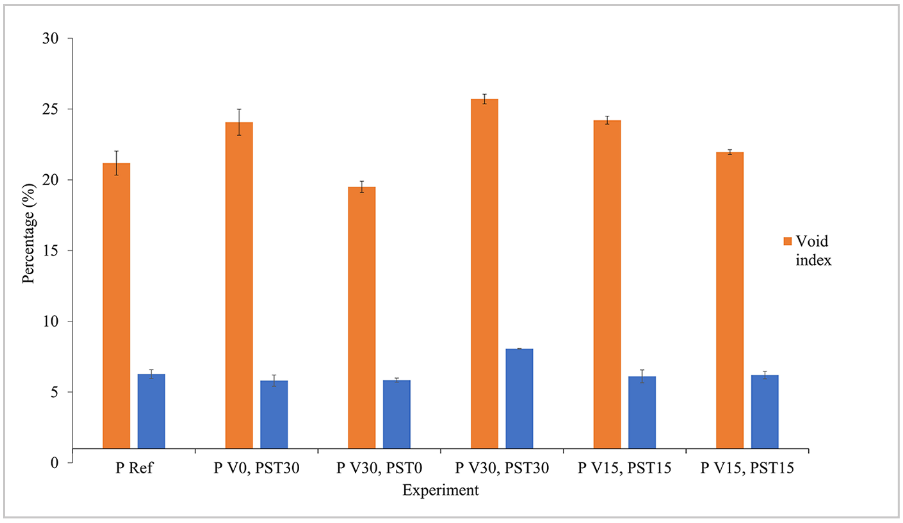

Figure 4 - Water absorption and voids index (Iv) of different paver compositions.

The result of a lower void rate can be explained by the inclusion of ground glass waste, causing the material to present granulometry in the optimal zone, which consequently occupies empty spaces in the mixture, resulting in the reduction of voids in the paver. Pavers with São Tomé stone wastes had a greater water absorption. This is explained according to Queiroz *et al.* (2018): São Tomé stone is porous. Therefore, complementary studies must be carried out to investigate the effect of adding São Tomé stone waste on water absorption in pavers. In addition, studies with different proportions of cement or compaction tests can be carried out to produce the pavers in order to mitigate the impact of the higher water absorption in the São Tomé stone waste.

The results obtained from ANOVA (Table 3) show that all factors and the interaction, presented a p-value< 0.10. It is also noticed that the interaction factor 1 by 2, that is, the glass waste with the São Tomé stone waste, presented the highest F-value (22.70277), affording this factor a better statistical significance, separately.

Table 3 - Results of the ANOVA for the water absorption of the pavers after 50 days.

Factor	SS	df	MS	F-value	p-value
(1) Glass waste	0.828100	1	0.828100	10.47013	0.083694
(2) São Tomé stone waste	0.774400	1	0.774400	9.79117	0.088747
1 by 2	1.795600	1	1.795600	22.70277	0.041336
Erro	0.158183	2	0.079092		
Total SS	3.556283	5			
R-squared = 0.95552					

Figure 5 shows the Pareto chart almost reaching 90% reliability. It is noticed that the factors for the São Tomé stone and glass waste reached statistical significance.

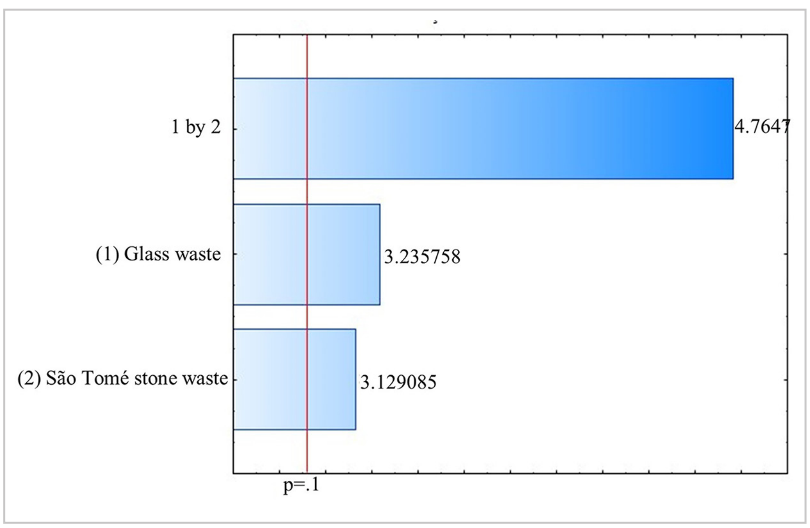

Figure 5 - Pareto chart of factors (1) Glass waste,
(2) São Tomé stone waste and 1 by 2 for water absorption after 50 days.

Figure 6 shows that increasing both São Tomé stone waste and glass waste increases the water absorption of pavers.

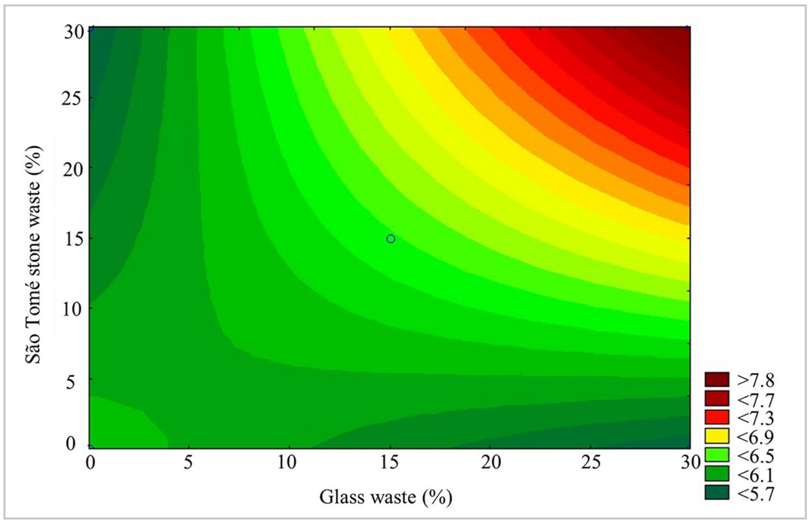

Figure 6 - Response Surface graph for water absorption of the pavers after 50 days.

Equation 1 is the regression equation that describes the behavior of water absorption with the addition of São Tomé stone waste and glass waste after 50 days, where Z is the water absorption, x_1 is the content of glass waste added in the paver and x_2 is the content of São Tomé stone waste added in the paver.

$$Z = 6.6 - 0.014x_1 - 0.015x_2 + 0.003x_1.x_2 + 0.26 \quad (1)$$

Figure 7 shows that the average compressive strengths of the pavers increased with increasing curing time. The paver P V30, PST30 reached an average compressive strength of 17.7 MPa and a standard deviation of 1.49 MPa after 28 days, these being lower values than those of the other pavers.

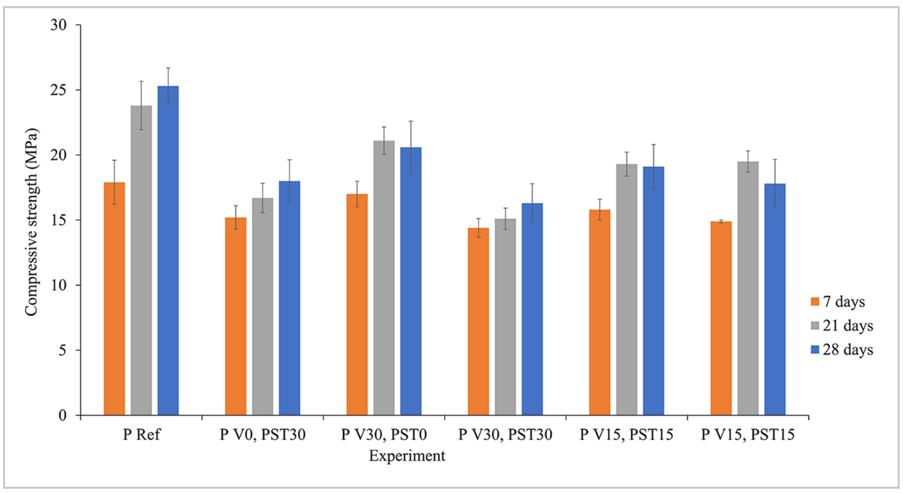

Figure 7 - Compressive strength of paver samples at 7, 21 and 28 days.

This can be explained by the fact that the composition contains a higher content of substitution of São Tomé stone and glass waste. In addition, this result is explained by the fact that the paver P V30, PST30 presented a higher value of voids index (25.71%) and water absorption (8.06%), which contributed to the reduction in resistance. P V30, PST0 obtained the second highest value of average resistance to compression at 28 days due to the lowest values of water absorption (5.84%) and voids index (19.50%). Table 3 presents average percentage values of compressive strength achieved according to the ages of the experiments compared with the reference paver. Table 4 demonstrates that the pavers reached above 73.3% of the average final resistance of 28 days after 7 days. Relating the pavers with waste to the reference paver, it was possible to reach 85% of the average final resistance of 28 days after 7 days.

Table 4 - Compressive strength of the pavers at 7-days and 28 -days.

Experiment		P_{ref}	$P_{V0, PST30}$	$P_{V30, PST0}$	$P_{V30, PST30}$	$P_{V15, PST15}$	$P_{V15, PST15}$
percentages	7/28 days	73.3	77.95	79.5	85.0	80.0	76.0
Related (%)	P Ref	-	73.3	84.59	66.54	77.44	73.31

The results of ANOVA for the compressive strength results after 21 days (Table 5) reached a p-value < 0.1 for both wastes, and R-squared of 0.99817. This indicates that the results are statistically significant.

Table 5 - Results of the ANOVA method for compressive strength at 21 days.

Factor	SS	Df	MS	F-factor	p-value
(1) Waste glass	4.62250	1	4.62250	105.6571	0.009332
(2) São Tomé stone glass	42.90250	1	42.90250	980.6286	0.001018
1 by 2	0.30250	1	0.30250	6.9143	0.119295
Error	0.08750	2	0.04375		
Total SS	47.91500	5			
R-squared = 0.99817					

Figure 8 shows the Pareto chart almost reaching 90% reliability. Also, it is noticed that the factors São Tomé stone and glass wastes reached statistical significance.

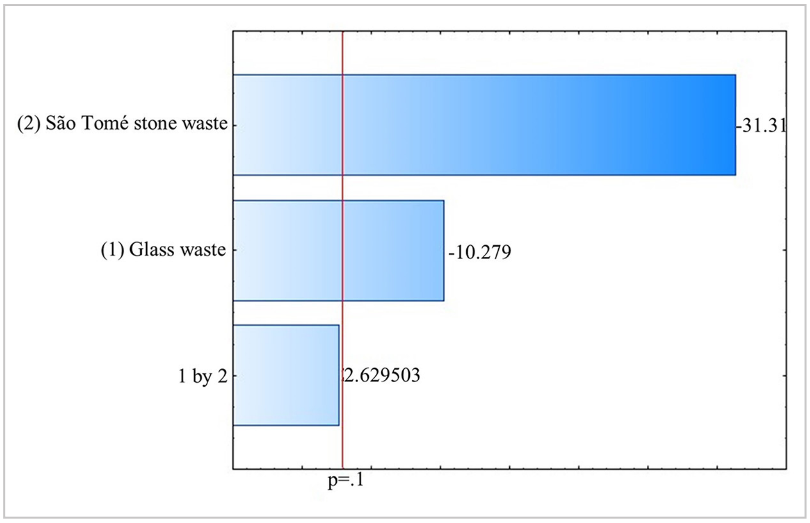

Figure 8 - Pareto chart of factors (1) Glass waste, (2) São Tomé stone waste and 1 by 2 for compressive strength after 21 days.

Figure 9 shows the response surface graph that represents the relationship between the averages of the compressive strength results after 21 days of the pavers. Adding glass waste can make pavers reach a greater compressive strength at 21 days than that achieved by adding São Tomé stone. The addition of both wastes decreases the compressive strength compared to that of the reference specimen.

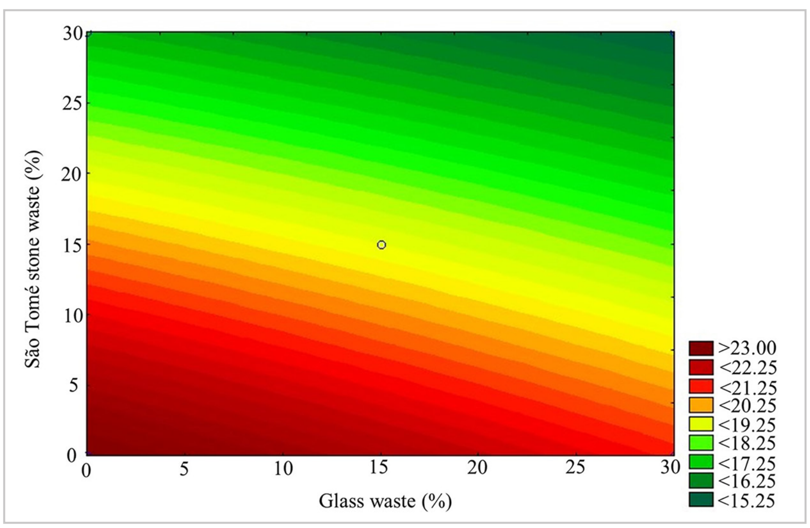

Figure 9 - Response surface graph for compressive strength of the pavers containing São Tomé stone waste and glass waste after 21 days.

The regression equation 2 shows the relation compressive strength (Z) in MPa at 21 days with addition of glass waste (x_1) and São Tomé stone waste (x_2).

$$Z = 23.875 - 0.090x_1 - 0.237x_2 + 0.200 \quad (2)$$

Figure 10 shows that the paver P ref reached a temperature of 48.06 °C, whereas P V30, PST30 reached a temperature of 45.06 °C, followed by P V30, PST0 at 45.90 °C, that is, a reduction in the maximum temperature of 6.25%. One of the reasons that led to the reduction in heat absorption is the lower thermal conductivity of pavers with increased porosity (Li *et al*., 2022).

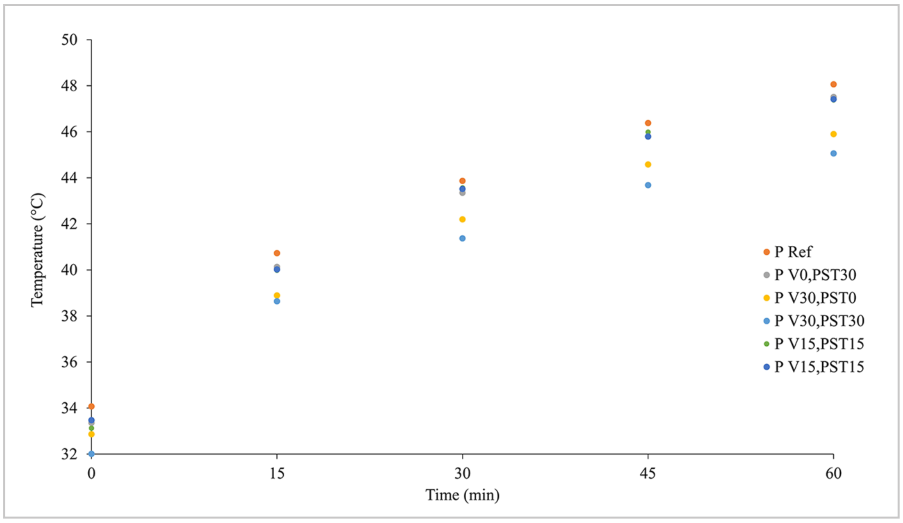

Figure 10 – Thermal representation of the pavers subjected to artificial light radiation.

The lower thermal conductivity suggests a greater difficulty in the diffusion of heat to the interior of the specimen, which suggests a lower temperature of the paver when exposed to heat. Figure 11 shows that the pavers with the best performance in sunlight were P V30, PST0 and P V30, PST30, reaching temperatures of 51.23 °C and 51.37 °C, respectively. P ref reached the highest temperature, 54.20 °C. The difference in temperature between the pavers with the best and worst performance is approximately 3 °C.

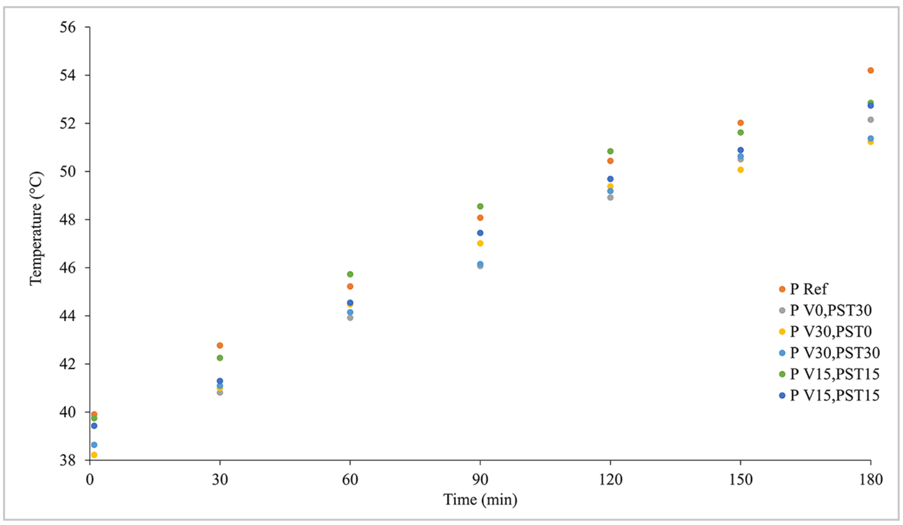

Figure 11 - Thermal representation of the pavers subjected to sunlight radiation.

What is observed in traditional pavements is that during exposure to sunlight, the temperature of the pavement is higher than the ambient temperature, which creates a sensation of heat greater than that recorded. It was observed that the pavers containing wastes reached lower final temperature than the paver without the addition of residue. This implies in a decrease in thermal sensation in places where this product is being used.

4. Conclusions

The chemical analysis results of glass and São Tomé stone wastes showed 71.90% and 86.09% SiO_2, respectively. After the comminution process, the granulometric analysis of the glass waste reached a fineness modulus of 2.87, whereas the São Tomé stone waste reached a fineness modulus of 3.03. Thus, the milling process enhanced the use of wastes in the composition of pavers.

The P V30, PST0 paver showed the best solar thermal absorption, with a reduction of 5.5% in temperature. P V30, PST0; P V30, PST30; and P V0, PST30 were 3, 2.8, and 2.0 °C cooler than the reference paver, respectively. The glass waste, which partially replaced the fine aggregates, absorbed less heat in the pavers. In the artificial measurement, the paver P V30, PST30 achieved a 6.25% reduction in temperature compared with the reference paver.

The standard mix exhibited a higher mechanical resistance and the P V30, PST0 mix achieved 85% of the resistance of the reference paver. A reduction in mechanical resistance was observed with the replacement of glass waste and São Tomé stone waste. This reduction in strength could be attributed to the higher water absorption of the São Tomé stone waste. The glass, with its optimal granulometry, promoted the filling of empty spaces, thereby reducing the porosity, and contributing to the increase in resistance of the pavers in comparison to the other compositions. Thus, a possible application of the pavers produced in this study can be in paving pedestrian sidewalks, since this requires pavers with lower mechanical resistance.

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