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Compressive strength assessment bricks manufactured with Phosphogypsum in different dosages

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ABSTRACT. This research studies soil-compacted bricks using Phosphogypsum (PG) in their dosage. PG is the subproduct of the primary raw material used by the fertilizer industry, and its disposal is a challenge for the industry because of its large generation. Laboratory tests were performed to assess these bricks' physical characteristics. To obtain the bricks, two dosages were used: 4 and 7% of Phosphogypsum (PG) concentration. Bricks with no Phosphogypsum (PG) in their mixture were also assessed as a benchmark. The brick's physical characteristics were obtained for non-fired and fired bricks (900ºC for 96 hours in the oven). The results of the laboratory tests were analyzed through statistical analysis to explore the differences between the means for each studied condition (dosage and drying method). Furthermore, there was no statistical difference between the compressive strength of bricks manufactured with 4 and 0% PG, pointing out that until this percentage, the studied bricks did not show strength reduction with PG increasing. The fired bricks showed higher strength for all dosages than the non-fired ones. However, according to the Brazilian Technical Standards, all studied bricks presented enough strength for regular construction. Phosphogypsum (PG) for brick manufacturing can be an alternative way for its disposal, which can help mitigate the civil construction environmental impacts.

Keywords: civil construction; sustainable materials; bricks; recycling; industrial wastes.

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Introduction

Civil construction has become a prominent consumer of natural resources, among all economic activities, due to its constant growth, mainly associated with urban areas. Many researchers have attempted to develop viable solutions to reduce the environmental impact of civil construction. Among these solutions, the use of (industrial) solid wastes to replace natural raw materials for manufacturing construction materials can be pointed out. However, industrial solid waste needs particular care in its management and disposal since it is often associated with potentially polluting substances (Fernandes, 2017; Mashifana, Okonta, & Ntuli, 2018). To reduce the generation of industrial solid wastes, it is essential to maintain proper management of the manufacturing processes, including destination and final disposal of those which sustainable principles should drive (Sampaio & Werlang, 2016).

Among industrial solid waste, phosphogypsum (PG) is the subproduct of the primary raw material used by the fertilizer industry: phosphoric acid (Cánovas, Macías, Péres-Lopez, Basallote, & Millan-Becerro, 2018). According to Campos, Costa, Nisti, and Mazzilli (2017) and Attalah, Metwally, Moussa, and Soliman (2019), PG can be classified as a Naturally Occurring Radioactive Material (NORM), which means that its reuse may pose risks to humans and the environment from the radiological protection point of view. PG (which is mainly composed of calcium sulfate dihydrate) consists of a waste that is generated by the production of phosphoric acid by wet processing of the phosphoric rock, formed mainly by apatite mineral ($Ca_5(PO_4)_3OH$)) with sulphuric acid. The PG is taken to a suspension with water and pumped to storage rafts, where it decants and dries out. The chemical equation of phosphoric acid production is as follows (Tsioka & Voudrias, 2020; Attalah et al., 2019).

$Ca_5F(PO_4)_3+5H_2SO_4+10H_2O \rightarrow 3H_3PO_4+5CaSO_4.2H_2O+HF$ (1)

Based on this equation, nearly 5 tons of PG ($CaSO_4.2H_2O$) are produced from 1 ton of phosphoric acid (H_3PO_4) (Chen, Zhang, Qi, Fourie, & Xiao, 2018; Ennacri & Bettach, 2018; Zhou, Gao, Shu, Wang, & Yan, 2012; Taybi, Choura, López, Aguacil, & López-Delgado 2009). PG is a powdery material with little or no plasticity, with particle density between 22.7 and 24.0 kN m^{-3} and bulk density between 9.0 and 17 kN m^{-3} (Yang, Zhang, & Yan, 2016). From the morphological point of view, PG is characterized by a crystal structure, mostly in rhombic and hexagonal forms. PG also contains impurities such as H_3PO_4, $Ca(H_2PO_4)$ H_2O, $CaHPO_42H_2O$, and $Ca_3(PO_4)_2$, residual acids, fluorides (NaF, NaF_2SiF_6, Na_3AlF_6, Na_3FeF_6, and CaF_2), sulfate ions, trace metals, and organic matter as aliphatic compounds of carbonic acids, amines, and ketones, adhered to the surface of gypsum crystals (Taybi et al., 2009).

Due to its low economic value for companies, PG usually ends up being landfilled or discharged into the environment without any prior treatment, thus resulting in environmental contamination and pollution of soil and water, including seawater (Amrani, Taha, Kchikach, Benzaazoua, & Hakkou, 2020). An estimated 100-280 million tons of PG have generated worldwide annually. Only 15% of these are recycled as soil stabilization amendments, fertilizers, and building materials, mainly due to their strong acidity (pH<3) and high moisture content (Attalah et al., 2019; Zhou et al. 2012). Approximately 3 billion tons of PG are stored in deposits of different sizes in over 50 countries (Campos, Costa, Nisti, & Mazzilli, 2017). Due to the possible acid and heavy metals infiltration, PG storage may cause soil and water pollution (Ajam, Hassen, & Neguigui, 2019; Yang et al., 2016;). The storage and management of PG are considered the main challenges facing the phosphoric acid production industries worldwide (Taybi et al., 2009). They require the mobilization of significant resources and occupy large land areas (Amrani et al., 2020; Amrani et al., 2020;).

In Brazil, PG is a severe environmental liability. The amount of PG generated as waste is about 4 to 6 times higher than the amount of phosphoric acid produced, making the storage and disposal of this waste product challenging, especially for fertilizer industries. According to Campos et al. (2017), Brazilian production of PG reaches 12 million tons per year. The industrial complex of Uberaba/Brazil, the biggest producer of phosphoric acid in Brazil, generates more than 3 million tons of PG per year: the PG waste is stored in a 1 million m^2 area in piles that are 30 m high. Another fertilizer industry in Catalão produced 2008 an amount of 600.000 tons of PG that is disposed of in landfills. Campos et al. (2017), comments that paper and cement industries and agriculture have reused only 10% of the PG produced by this industry.

The interest in PG as a source of secondary raw materials has increased over the past decade (Chernysh, Yakhnenko, Chubur, & Roubík, 2021). Initially, PG was considered mainly a construction, cement, road-building, and agricultural industry component (Ennacri & Bettach, 2018; Zhou, Yu, Shu, Li, Chen, & Wang, 2014). However, over the past 10-20 years, the focus has shifted, given the increase of anthropogenic pressure on the environment and the resulting shortage of natural sources of raw materials (Zhou et al., 2012). PG, which has many valuable elements, is considered a source of calcium, phosphorus, rare-earth elements, trace elements, and a mineral resource in technological and environmental protection processes. Research increasingly focuses on finding reliable and efficient ways to manage and reuse PG, especially in civil construction (Amrani et al., 2020; Ennacri & Bettach, 2018). In addition, an assessment of its radiological impact is required, mainly due to the radionuclides content and radon exhalation (Campos et al., 2017). Zhou et al (2012) point out that using PG for civil construction can be a valuable way to reduce the environmental impacts caused by this economic sector. Like Fernandes (2018), many authors point out that PG can be used for alternative construction materials manufacturing, including bricks, tiles, and mortar. According to Sun et al. (2023), phosphogypsum wastes (PG) have been proven recyclable in producing suitable aggregate and binder for concrete, with a substitution rate above 70 and 40% in the binder. The authors performed research to assess the mechanical characteristics of concretes made with high percentages of PG. According to the authors, PG concrete technology would find large-scale applications in recycling massive phosphogypsum waste. As another type of construction material made with PG, gypsum blocks are reported by Qin et al. (2023). As stated by the authors, Gypsum blocks are lightweight, heat-insulated, fireproof, and easy to construct, so it is an energy-efficient and environment-friendly building material. The authors also pointed out that PG for manufacturing bricks is an important use for this aste in civil construction. Men, Li, Cheng, and Zhang (2021) comment on using PG for stabilizing foundation soils for road base construction. The authors state that Adding PG can reduce the amount of cement used while satisfying the exact strength requirements, thus reducing construction costs. Muthukumar et al. (2022) developed and assessed a lightweight panel for lowcost housing constructions using concrete mixed com PG. The authors found that promising results were obtained with a decent increase in strength and durability, which shows that the material can be used effectively in the civil engineering industry.

Several studies have explored using PG in the base and sub-base of roads and embankments and as a final layer of earthworks to improve soil properties, minimize the possible environmental impacts caused by the disposal, and insert a new material on the market. However, the primary use of PG remains in cement manufacturing, where it substitutes natural gypsum (about 5%) (Ajam et al., 2019; Degirmenci, Okucu, & Turabi, 2007). Researchers have studied the possibility of using PG in construction materials such as raw blocks and fired bricks, and promising results have been found (Ajam et al., 2019; Zhou et al., 2012). In addition, PG can be reused with fly ash and Portland Cement in the building industry (Zhou et al., 2014). Such results suggest that PG can become an alternative raw material for the civil construction sector, reducing the impact of landfills close to the chemical industries.

For such applications, the natural radioactivity of PG, mainly from ^{226}Ra, remains a challenge (Mashifana, Okonta, & Ntuli, 2018). In addition, other radioactive elements derived from phosphate rocks may be present, such as Pb^{210}, Po^{210}, U^{238}, and U^{234} (Rachad, 2017). PG that exceeds 370 Bq kg^{-1} (10pCig^{-1}) of radioactivity has been banned from all uses by the USA Environmental Protection Agency (EPA) since 1992 (Rashad, 2017). In addition, the European Atomic Commission (EURATOM) prescribed a limit of 500 Bq kg^{-1} (13.5 pCig^{-1}). Despite such characteristics, however, Rashad (2017) points out that PG cannot be classified as toxic waste since PG elements are not corrosive and the average total concentration of elements classified as toxic (e.g., Ba, As, Cr, Cd, Hg, Pb, Se, and Ag) by the USA Environmental Protection Agency is lower than the EPA allowable limits for toxic, hazardous waste.

This study characterizes the physical parameters of fired and non-fired bricks produced with PG in their dosage. It also studies the influence of PG dosage on these physical characteristics. The main objective is to evaluate the potential use of PG as an alternative construction material, thus reducing the environmental impacts caused by this solid waste and civil construction activities.

Methodology

Laboratory tests for determination of physical properties of soils and bricks

A representative soil sample was collected at 1.5 m depth from the Experimental Field for Soil Mechanics at the University Nove de Julho, São Paulo, Brazil. The tests were conducted at the Soil Mechanics Laboratory and the Civil Construction Materials Laboratory at Universidade Nove de Julho in São Paulo, Brazil.

Testing soil samples with different PG proportions were prepared: soil + 0% PG, soil + 4% PG, and soil + 7% PG. It must be highlighted that proportions like soil+ 2% PG, soil +3% PG soil+5% PG, soil+ 6% PG, and soil +10% PG were also preliminarily tested; however, the obtained data were very statistically to the dosages: soil + 0% PG, soil + 4% PG, and soil + 7% PG. This way, the dosages showed in this paper consists on well-defined boundaries among all studied proportions.

To characterize the collected soil and the prepared testing samples, granulometric analysis tests and determination of consistency limits (Liquid Limit, Plasticity Limit) were conducted according to Brazilian Association of Technical Standards (ABNT, 2018) ABNT NBR 7181, (ABNT, 2017) ABNT NBR 6459, and (ABNT, 2016) ABNT NBR 7180, respectively. After the tests, the testing samples were classified by the Unified Soil Classification System (ASTM D 2487 - 06).

The PG material was donated by the Energy and Nuclear Research Institute (Ipen) in plastic bags sealed in dihydrate form. The PG producer's name will be omitted in this paper; however, it is in Minas Gerais/Brazil. Before its use, the PG was dried in an oven at 100ºC for 24 hours. Because of this drying, the PG was transformed from dihydrate to hemihydrate. The samples were prepared according to (ABNT, 2016) ABNT NBR 6457.

After classification, compaction tests were carried out with normal proctor energy for each of the mixtures (soil + 0% PG, soil + 4% PG, and soil + 7% PG) according to (ABNT, 2016) ABNT NBR 7182 to determine the maximum dry unit weight (γdmáx) and the optimum moisture content of the mixtures under study.

After that, bricks were compacted in each of the studied dosages. The bricks were subjected to compressive strength as recommended by (ABNT, 2005) ABNT NBR 13279 Compacted bricks were chosen instead of cylindrical specimens (L=2*D) once the main objective of this research was to make the proposition and the assessment of an alternative destination for PG that could be used in building constructions. Furthermore, the research also brings to light the differences between bricks' physical behaviour according to how they were manufactured (fired and non-fired).

The equipment used was a compressive testing machine EMIC — GR48, and the tests were performed at the Construction Materials Testing Laboratory at the State University of Campinas. The bricks were manufactured using a hydraulic press machine. In total, 60 bricks were compacted, 10 for each dosage for fired and non-fired bricks. The dimensions of the bricks were: 210 mm in length, 5 mm in thickness, and 100 mm in width. The bricks (fired and non-fired) were tested 14 days after their manufacturing. During this time, they remained in the laboratory, protected from natural weather conditions.

Descriptive statistical methods were used for data analysis, verification of data adherence to the normal distribution (Kolmogorov-Smirnov and Shapiro-Wilk tests), homogeneity analysis tests of variances (Levene test), ANOVA, and post hoc Tukey's HSD test. For data not adhering to the normal distribution, the Kruskal-Wallis non-parametric test was used, and the Mann-Whitney test was performed as a post hoc test.

Determination of activity concentration of radionuclides and effective annual dose of radiation due to external exposure

All building materials contain varying amounts of natural radionuclides. In the case of PG, this material contains a concentration of natural radionuclides, which, depending on its magnitude, can cause an increase in the radiation dose when used as building material in a dwelling type structure.

The assessment of the effective annual dose inside a residence was established by the methodology proposed by Turhan, Bayan, and Sen (2008), Turhan and Gunduz (2008), based on the concept of a standard room. First, the absorbed dose is calculated using the following equation:

$$DR = (qRA.CRA + qTH.CTH + qk.CK).mi \qquad (2)$$

Where DR = rate of dose absorbed in the air (nGy.h-1); qRA, qTH, qK = conversion factors for the concentration of ^{226}Ra, ^{232}Th, and ^{40}K, respectively; CRA, CTH, CK = activity concentration of ^{226}Ra, ^{232}Th, and ^{40}K, respectively; mi = percentage fraction of mass of "i" type building material in a standard room.

The following equation can calculate the effective annual external dose:

$$E = DR.T.f.FCD.0.000001 \qquad (3)$$

Where E = effective annual dose due to external exposure (mSv a^{-1}); DR = rate of dose absorbed in the air (nGy h^{-1}); T = 8760 hours $year^{-1}$; f = occupancy factor of the residence; DCF = conversion factor from dose absorbed in the air to effective dose (Sv Gy^{-1}).

Results and discussions

Physical characterization of the materials

The properties of the soil samples are shown in Table 1. According to the Unified Soil Classification System, the soil samples can be classified as a CH type.

Table 1. The properties of studied materials and dosages.

Average properties	Soil Sample
Classification (USCS)	CH
% passing through sieve #200	>50%
Liquid Limit (LL)	52%
Plasticity Index (PI)	29%
Optimum moisture content	27.6%
Maximum dry unit weight (γdmáx)	14.9 kN m^{-3}
Average properties	**Soil + 4% PG**
Liquid Limit (LL)	50%
Plasticity Index (PI)	17%
Optimum moisture content	27.0%
Maximum dry unit weight (γdmáx)	14.8 kN m^{-3}
Average properties	**Soil + 7% PG**
Liquid Limit (LL)	47%
Plasticity Index (PI)	15%
Optimum moisture content	25.0%
Maximum dry unit weight (γdmáx)	14.8 kN m^{-3}

Average properties	PG
% passing through sieve #200	>75%
Liquid Limit (LL)	---
Specific gravity (γs)	22.8 kN m^{-3}
Bulk density (γnat)	15.3 kN m^{-3}
Plasticity Index (PI)	---
Natural moisture content	40%

According to Table 1, the physical parameters figured out for PG are close to those reported by Men et al. (2021) and Muthukumar (2022). Table 2 shows the activity concentration of ^{226}Ra, ^{232}Th, and ^{40}K obtained next in the PG material, as measured by the researchers.

Table 2. The samples' activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K (Bq kg^{-1}) were taken.

Sample	^{226}Ra	^{232}Th	^{40}K
Phosphogypsum A	1277 ± 39	445 ± 14	< 26
Clayey Soil (CH)	64 ± 2	120 ± 6	155 ± 23

Ultimate compressive strength was obtained for the fired bricks

The ultimate compressive strength values are shown in Table 3. The linear correlations between PG percentage and compressive strength are shown in Figure 1.

Table 3. Results of ultimate compressive strength for each PG dosage.

Dosage	N	Mean (MPa)	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum (MPa)	Maximum (MPa)
					Lower Bound	Upper Bound		
0%	10	12.92	1.64	0.73	10.87	14.96	11.5	15.4
4%	10	13.72	2.05	0.92	11.16	16.27	12.3	17.3
7%	10	4.86	0.88	0.39	3.76	5.95	3.9	6.1
Total	30	10.5	4.40	1.13	8.06	12.93	3.9	13.3

N=number of specimens (fired bricks)

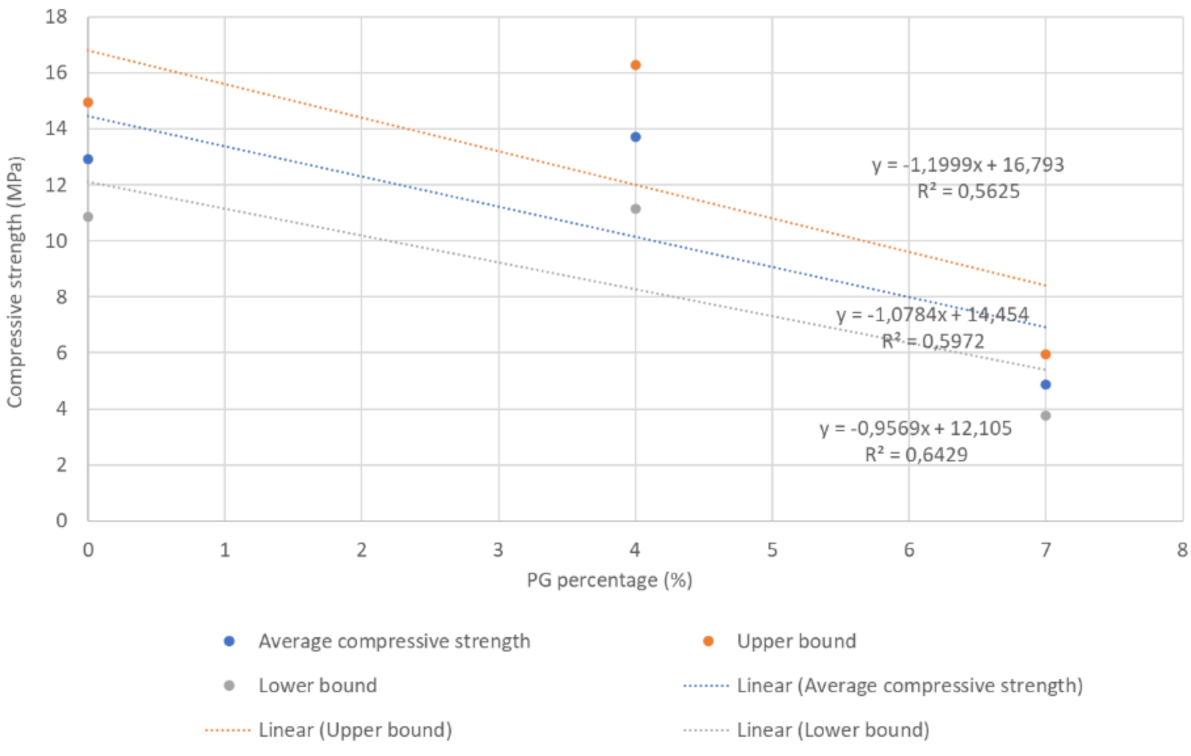

Figure 1. Linear correlation between phosphogypsum dosage and compressive strength (fired bricks).

As reported in Table 3, the compressive strength decreases for a high PG percentage. The Kolmogorov-Smirnov and Shapiro-Wilk tests did not reject normality ($p > 0.05$), but Levene's test showed nonhomogeneous variances. Thus, the Kruskal-Wallis test was performed. According to the Kruskal-Wallis test, the PG percentages in each group influenced the compressive strength of the fired bricks. The trend of strength reduction when the PG percentage gets higher was verified again. The Mann-Whitney posthoc test was performed for three comparisons: 0%PG versus 4%PG, 0% PG versus 7%PG, and 4% PG versus 7% PG. The results of the test were: s = 0.10 ($p > 0.05$), s = 0.01 ($p < 0.05$), and s = 0.012 ($p < 0.05$), respectively. These point to no difference between 0 and 4% PG and statistically significant differences between these groups and 7% PG. Thus, it can be observed that the compressive strength percentage presents a notable influence at 4% of PG; however, between 4 and 7% of PG concentration, the compressive strength decreases.

The compressive strength reducing due PG increasing is already reported by researchers like Ajam et al. (2019), Zhou et al. (2012) and Anuradha (2022). However, Figure 1 shows that the decreasing trends between compressive strength and PG percentage were not well adjusted to a linear behavior. This can be realized according to the correlation coefficients obtained (R^2).

Ultimate compressive strength obtained for the non-fired bricks.

The results forl the ultimate compressive strength of non-fired bricks are shown in Table 4. The Linear correlations between PG percentage and compressive strength are shown in Figure 2.

Table 4. Results of ultimate compressive strength for each dosage in non-fired bricks.

Dosage	N	Mean (MPa)	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum (MPa)	Maximum (MPa)
					Lower Bound	Upper Bound		
0%	10	3.64	0.73	0.32	2.72	4.55	2.6	4.3
4%	10	2.92	0.22	0.10	2.63	3.20	2.6	3.2
7%	10	2.46	0.27	0.12	2.12	2.79	2.1	2.8
Total	30	3.00	0.66	0.17	2.63	3.37	2.1	4.3

N=number of specimens (fired bricks).

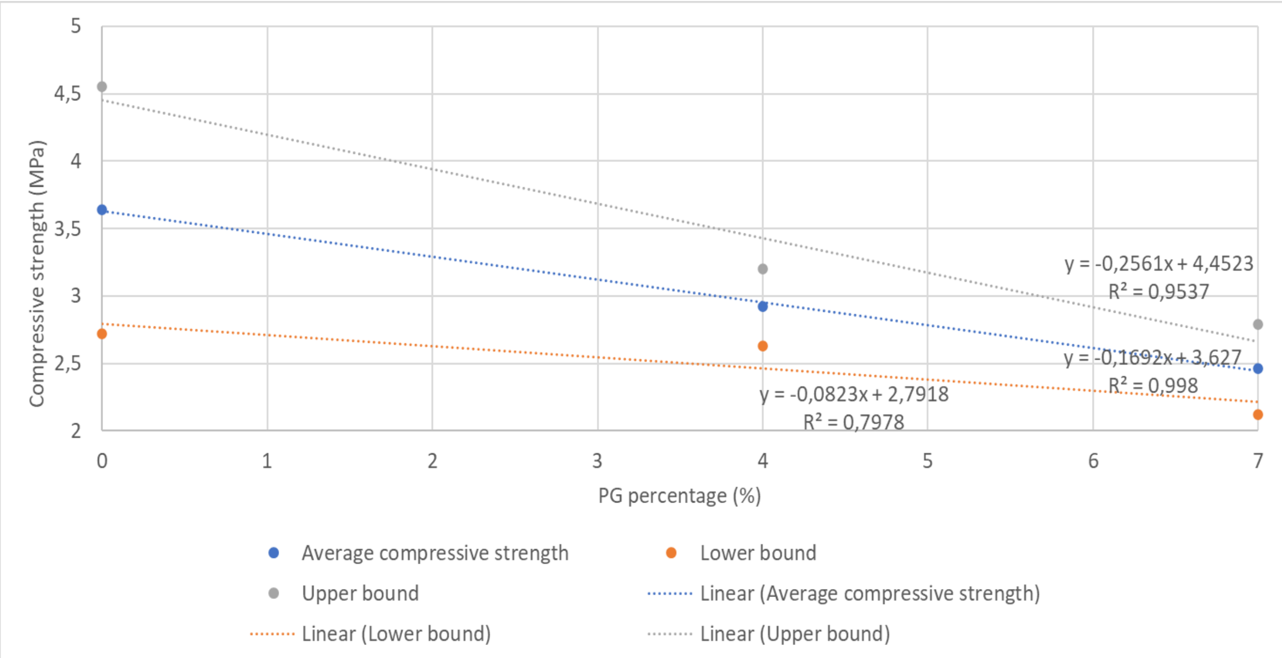

Figure 2. Linear correlation between phosphogypsum dosage and compressive strength (non-fired bricks).

The ultimate compressive strength was lower at a high percentage of PG as figured out concerning fired bricks. Kolmogorov-Smirnov and Shapiro Wilk tests were run and showed $p > 0.05$. However, according to Levene's test, the variances are not homogeneous. Thus, the Kruskal-Wallis test was performed. The results point to a significant difference among the studied groups ($p < 0.05$), indicating that the PG percentage in each group influences the non-fired bricks' ultimate compressive strength. The Mann-Whitney posthoc test was run, and three conditions were considered: 0% PG versus 4% PG, 0% PG versus 7% PG, and 4% PG versus 7% PG. The test returned the following results: s = 0.15 ($p > 0.05$), s = 0.01 ($p < 0.05$), and s = 0.013 ($p < 0.05$), respectively. These point to no difference between 0% PG and 4% PG and statistically significant differences between these groups and 7% PG. Thus, the compressive strength presents a notable influence at 4% of PG concentration; however, the compressive strength decreases between 4 and 7% of PG concentration. Figure 2 shows that the decreasing trends between compressive strength and PG percentage were well adjusted to a linear behavior. This can be realized according to the correlation coefficients obtained (R^2).

Comparison between ultimate compressive strength obtained for fired and non-fired bricks.

After determining the compressive strength values for non-fired and fired bricks, they were compared. Thus, a test for paired samples was carried out to determine if the fired process used for the bricks influenced the compressive strength of the studied bricks. The performed test results are shown in Table 5.

Table 5. Test of ultimate compressive strength for paired samples of fired and non-fired bricks.

Pair	Description	Mean	Std. Deviation	Std. Error	95% Confidence Interval of the Difference		t	df	s
					lower	upper			
1 (0%PG)		-9.28	1.51	0.67	-11.16	-7.39	-13.6	4	0.000
2 (4%PG)		-10.8	1.87	0.83	-13.12	-8.47	-12.8	4	0.000
3 (7%PG)	CNFx CF	-2.40	0.83	0.37	-3.43	-1.36	-6.40	4	0.003

CNF - Ultimate compressive strength for non-fired bricks; CF - Compressive strength for fired bricks.

Table 5 shows that the difference between the two conditions' average values was significant enough not to be random. The table provides the mean difference between the scores: Pair 1 = -9.28; Pair 2 = -10.80; Pair 3 = -2.40. The table also shows the standard deviation of the differences and the standard error between the specimens' scores in each condition. If the values of t are negative, the average of the compressive strengths for fired bricks is less than the average of the compressive strengths for non-fired bricks. Therefore, it is concluded that after the specimens pass through the oven, they present greater resistance to compression. The 95% confidence intervals do not contain zero (both limits are negative), indicating that the value of the average difference is unlikely to be zero. Therefore, one can be confident that the data does not represent random samples from the same population. To calculate the effect size r and to convert a t-value to an r-value, the following equation was used:

$$r = \sqrt{\frac{t^2}{t^2+gl}} \quad (4)$$

The effect size values r for all three pairs are > 0.95, indicating a substantial effect (above 0.5). Therefore, this effect is also prominent in addition to being statistically significant.

The effective dose of external exposure

The activity concentration of ^{226}Ra, ^{232}Th, and ^{40}K (Bq kg^{-1}) and the values of DR and E were determined for the material studied with the highest dosage of PG, that is, 7% concentration. The values obtained are presented in the following Tables.

Table 6. The samples were concentrated at ^{226}Ra, ^{232}Th, and ^{40}K (Bq kg^{-1}).

Sample	Concentrations (Bq kg^{-1})		
	^{226}Ra	^{232}Th	^{40}K
Soil + PG (7%)	173 ± 6	146 ± 7	159 ± 23

Table 7. The average value of DR (nGy.h^{-1}) and E (mSv a^{-1}) was obtained for brick with 7% PG.

Sample	DR (nGy.h^{-1})	E (mSv a^{-1})
Soil + PG (7%)	21.06	0.10

The values of E per year recommended by CNEN - Brazilian National Nuclear Energy Commission, by the European Commission, and by UNSCEAR - United Nations Scientific Committee on the Effects of Atomic Radiation are, respectively, E = 1.0 mSv; E = 0.3 mSv and E = 0.48. The material studied in this research had an E value lower than those recommended by these institutions.

Conclusion

Concerning the analyzed data, it is possible to notice when statistically analyzing that the bricks with mixtures of soil with 4% phosphogypsum do not present significant differences compared to those without the addition of phosphogypsum. This behavior occurred for both fired bricks and non-fired bricks.

Another essential piece of information is that, although soil mixtures with 4% phosphogypsum are statistically equivalent to mixtures without the addition of phosphogypsum, soil mixtures with 7% phosphogypsum can also be used, as they have adequate compressive strength according to technical standards.

The ABNT NBR 15270-1/2017 standard presents the requirements for the manufacture of blocks and ceramic bricks for masonry. According to this, the mixture with a 4% concentration of phosphogypsum can be used for solid bricks for sealing class 40. In addition, this mixture can also be used for solid structural bricks of classes 60, 80, 100, and 120. In the case of the mixture with a 7% concentration of phosphogypsum, it can be used to manufacture solid bricks for class 40 sealing.

Thus, although there are significant differences between compressive strengths when comparing fired and non-fired bricks, both can be used in the construction of buildings. In this way, this research brings to light a new alternative for the destination of phosphogypsum, as well as for the reduction of the housing deficit, since, as it consists of a residue not used by industry, phosphogypsum tends to present itself as more economical than the natural material extracted from deposits, which would allow cheaper residences. Furthermore, the use of phosphogypsum in the studied dosages also provides a technically viable alternative for its final destination and reduces the environmental pressure on deposits of natural materials. From this example, reducing the piles of phosphogypsum incorporated in manufacturing bricks becomes viable as it will also reduce the amount of raw material extracted from deposits for ceramic use.

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