CHEMICAL ENGINEERING TRANSACTIONS

VOL. 100, 2023

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Sauro Pierucci, Flavio Manenti

ISBN 979-12-81206-03-8; **ISSN** 2283-9216

DOI: 10.3303/CET23100016

Bricks Made from Glass Residues: a Sustainable Alternative for Construction and Architecture

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The reuse of glass discarded as waste contributes to minimising pollutants in the environment, especially in water and air, in the first case by reducing the presence of glass in the receiving bodies, and in the second by reducing CO_2 emissions into the air by ceasing to manufacture glass. Therefore, the objective of the research was to elaborate bricks having as constituent components cement, coarse sand and recycled glass waste previously conditioned by crushing to a suitable granulometry and characteristics as established in the Peruvian Technical Standard E.070 Masonry for the manufacture of bricks. With 252 kg of the aforementioned material, 180 bricks were made, testing different proportions of constituent material, the best result being 1:3:2 (cement, coarse sand and glass). Bricks were obtained that complied with the characteristics of dimensions, warpage, absorption and compression. The elaboration of this type of bricks will contribute to a sustainable construction activity and an environmentally sustainable architecture.

1. Introduction

Today's society is consumerist, satisfying its needs through the acquisition of different products such as food, clothes and others that are part of its development. The consumption of these products generates waste that in the end is discarded, generating environmental pollution (Fanarraga L. et al., 2022; Morales A. et al., 2022; Tarazona L. et al., 2021). For this reason, the aim is to raise awareness among the population about recycling, in order to minimise the negative effects of waste generation.

It is important to address this issue because, based on the problem, sustainable solutions for the environment have been proposed, where waste is reused to generate a by-product. To this, in the research of Krishnan et al. (2017) reused waste from water treatment as a plasticizing mixture with laterite soil for the clay brick manufacturing process. Vaccari et al. (2012) mentioned that sludge from soil washing is desirable from an economic point of view, and are materials that could be used on an industrial scale instead of virgin silt and clay to produce stabilized soil for road construction or in brick manufacturing.

European countries consider glass as a valuable material, as they use it for the manufacture of by-products, allowing them to reduce the pollution that afflicts the environment and health (Wang 2019). Sweden has achieved 90% of glass recycling, by investing in bottle containers and raising consumer awareness, as well as providing high quality secondary raw materials (Mantovani et al., 2018). Peru does not have good solid waste management; only 1.9% of solid waste is reusable, being plastics, glass, cardboard, among other waste (MINAM 2018). In the city of Lima in Peru, an average of 8202 tonnes/day of waste is generated and it is expected that by 2034 this amount will double (Diario Correo, 2016). Waste production according to zones is as follows: Lima centre 0.71 kg/day per inhabitant, Lima North with 0.65 kg/day per inhabitant, Lima East with 0.63 kg/day per inhabitant and in Lima South with 0.59 kg/day per inhabitant (Municipalidad Metropolitana de Lima, n. d.).

Glass can be very harmful to the environment, as white glass takes more than 4,000 years to decompose (Yang 2020). In the absence of a culture of recycling, they are disposed of directly in rubbish bags and often broken,

Paper Received: 6 January 2023; Revised: 18 March 2023; Accepted: 20 May 2023
Please cite this article as: Teran Mejia C.I., Alvarado Susanibar C.E., Castaneda-Olivera C.A., Jave Nakayo J., Benites-Alfaro E., Cabrera Carranza C.F., 2023, Bricks Made from Glass Residues: a Sustainable Alternative for Construction and Architecture, Chemical Engineering Transactions, 100, 91-96 DOI:10.3303/CET23100016

causing cuts to people in charge of collection or even being out in the open can cause damage to anyone else who is not involved in this work (Reyes et al., 2015).
The environment needs changes and strategies to reduce the agglomeration of solid waste, ensuring the greatest amount of glass recycling. Therefore, the main objective of this research was to elaborate bricks based on disposable glass, determining the adequate proportion of the mixture of the components for the elaboration of bricks. In addition, the physical and mechanical properties of the bricks were analysed and compared with the values established in the Peruvian Technical Standard E.070 Masonry (Gobierno del Perú, 2020). At a social level, this proposal benefits low-income areas, as buildings with these bricks will not require much cost. An example is the district of La Molina in Lima, Peru, where 3200 glass bottles were collected, processed and transformed into sand for reuse in benches, which have been placed in various parks, squares and public places in the district (Municipality of La Molina, 2021).

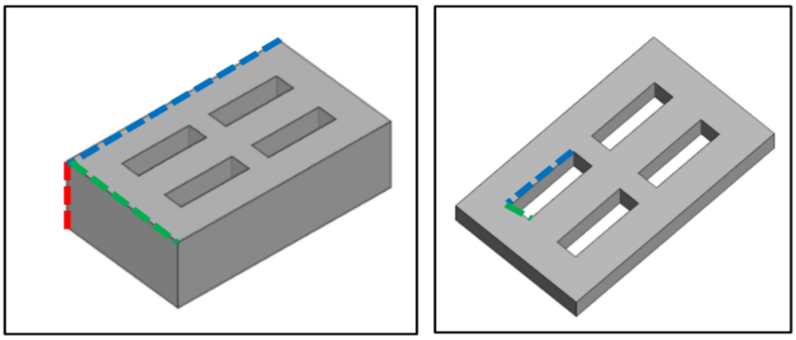
2. Materials and methods

2.1 Collection of the constituent components

240 clear and dark glass bottles were recycled. These bottles were washed and dried at room temperature (23°C). The glass bottles were then crushed, resulting in 257 kg of crushed glass. Of the material obtained, 252 kg were used to make bricks, and 5 kg were used for particle size analysis.
The binder material (Sol Portland Cement Type I) and the coarse sand (less than 2mm) were obtained commercially in the city of Lima, Peru.
The granulometry and appropriate characteristics of the constituent components followed the Peruvian Technical Standard E.070 Masonry (NTP E.070) for the manufacture of bricks.

2.2 Production of the bricks

For the production of the bricks, mixtures with the proportions 1:3:2 and 1:3:3 for the constituents cement/coarse sand/crushed glass were used. Subsequently, water was added to the mixture little by little, until the texture of the mixture was elastic and free of lumps. The mixture was then transferred to the brick mould, and the mixture was compacted well to cover all the spaces and avoid voids. This process was carried out with a designed mould (Figure 1). The bricks were subsequently demoulded in a clean, flat and ventilated area, and the bricks were left to set for 1 day. The next day, the bricks were arranged in stacks of 4 for curing and kept moist for 1 week; they were watered twice a day with potable water. From the 8th day, the bricks were left to dry over a period of 28 days.



-----	Height	8.5cm
-----	Width	13 cm
-----	Length	22 cm

-----	Width	2 cm
-----	Length	7 cm

Figure 1: Design of the mould for the production of the bricks

2.3 Physical and mechanical properties of the bricks

After 28 days, the bricks were dry, and physical and mechanical properties tests were carried out thereafter. These tests are shown in Table 1, and were carried out at 14 and 28 days after the bricks had dried for each mix proportion of the constituents. The values obtained in each test were compared with those established in the Peruvian Technical Standards.

Table 1: Physical and mechanical tests on bricks

Properties	Standard	Test	No. of samples
Physical	NTP 399.604	Dimensional variation (mm)	10
		Absorption (%)	5
	NTP 399.613	Warpage (mm)	10
Mechanical	NTP 399.604	Compression test in masonry unit (Kg/cm2)	5
	NTP 399.605	Compression test in masonry piles (Kg/cm2)	15

3. Results and discussion

3.1 Granulometric analysis of the recycled glass

The particle size of the recycled glass complied with the specifications indicated according to NTP E.070. Of the 5 kg of crushed glass, 3.9% of the material passed the No. 4 mesh, with most of the crushed glass being retained on this mesh (see Table 2).

Table 2: Granulometric analysis

Sieve	Opening (mm)	Partial retained (%)	Accumulated (%)	
			Retained	Pass
3"	75.00	-	-	
2"	50.00	-	-	
1 1/2"	37.50	-	-	100.0
1"	25.00	1.4	1.4	98.6
3/4"	19.00	14.1	15.5	84.5
1/2"	12.50	33.0	48.5	51.5
3/8"	9.50	21.4	70.0	30.0
1/4"	6.30	19.2	89.1	10.9
No. 4	4.75	7.0	96.1	3.9
Bottom		3.9		

3.2 Production of the bricks

The mixture with the proportion 1:3:2 was the most suitable for the production of bricks from recycled glass. Figure 2 shows the handmade bricks, which had the right characteristics to be used as a building material. Thus, recycled glass can be a partial substitute for the coarse aggregate (gravel) used for the manufacture of conventional bricks made of concrete. Similar research also produced bricks from waste glass powder as a partial substitute for clay in bricks (Tripathi and Chauhan 2021). Xin et al. (2023) investigated bricks produced from waste-contaminated glass dust as a substitute for clay, taking into account environmental impact and microstructural investigations, and showed that the production of these bricks is highly energy efficient. Other authors such as Hasan et al. (2021) also studied recycled glass as a solution to the depletion of natural clay.

Figure 2: Recycled glass bricks

3.3 Physical and mechanical properties of bricks

The compilation of physical and mechanical test results on the bricks at 14 and 28 days of drying for the mixes with the proportions 1:3:2 and 1:3:3 is shown in Table 3 and Table 4. These results were compared according to the values established in the Peruvian Technical Standard E.070 Masonry for the manufacture of bricks.

In the mix with the 1:3:2 proportion (Table 3), most of the bricks have a type V classification with respect to the results of the dimensional variation test, except for the results obtained at 28 days of life, which had a type II classification. These variations are due to the fact that it has been elaborated in an artisanal way and certain changes may occur that will not be as accurate as those that are elaborated in an industrial way (Pérez C., 2016). On the other hand, Gallardo M. (2021) mentions that by pouring excessive water into the mixture and then demoulding the bricks, they will be too wet and will not have sufficient support, in some cases they will break and in others the dimension will be reduced, since the water that drains from the brick drags part of the mixture vertically, causing the nominal height measurement to vary with respect to the real one. For the warping test, the classification of brick V and IV is given for 14 and 28 days of life, respectively. These results have not been constant, however, there is not too much variation. Castillo and Lopez (2018) indicate that the warping is a consequence of the production process, specifically for the demoulding stage, as many times the corners are stuck in the moulds, which produces deformations in the units. In the tests corresponding to the absorption, it was complied with the specifications of the NTP E.070, obtaining a minimum value of 7.2%. With regard to the mechanical properties, the best results were obtained after 28 days of life of the bricks, with the highest classification of brick type III. For the company Aceros Arequipa (2020), the concrete bricks should have a classification of brick V, in order to comply with the characteristic of resistance and high durability. However, the results obtained are not discouraging, as they are within the ranges established in the standard, and the resistance improved from 58.96 kg/cm^2 to 98.16 kg/cm^2 over the days. Finally, the pile compression test passed the minimum value required in NTP E.070 (35kg/cm^2). This indicates that the bricks will not only be used for walls but will also serve as a load-bearing wall that can support arches, beams and the structure of a building.

Table 3: Compilation of the results for the mixture with the proportion 1:3:2

Type	14 days of life									
	Variation of the dimension (maximum in percent)						Warpage	Obtained	Compressive strength per unit / kg/cm^2	Obtained
	More than 150 mm	Obtained	Up to 100 mm	Obtained	Up to 150 mm	Obtained				
Brick I	± 4	±0.45	± 8	±1.17	± 6	±0.77	10	2.4	50	58.96
Brick II	± 4	±0.45	± 7	±1.17	± 6	±0.77	8	2.4	70	58.96
Brick III	± 3	±0.45	± 5	±1.17	± 4	±0.77	6	2.4	95	58.96
Brick IV	± 2	±0.45	± 4	±1.17	± 3	±0.77	4	2.4	130	58.96
Brick V	± 1	±0.45	± 3	±1.17	± 2	±0.77	2	2.4	180	58.96
Absorption (not more than 22%)	10.1 %									
Compressive strength per piles / kg/cm^2 (minimum 35 kg/cm^2)	47.3 kg/cm^2									
Type	**28 days of life**									
	Variation of the dimension (maximum in percent)						**Warpage**	Obtained	**Compressive strength per unit / kg/cm^2**	Obtained
	More than 150 mm	Obtained	**Up to 100 mm**	Obtained	**Up to 150 mm**	Obtained				
Brick I	± 4	±0.32	± 8	±5.88	± 6	±0.15	10	2.6	50	98.16
Brick II	± 4	±0.32	± 7	±5.88	± 6	±0.15	8	2.6	70	98.16
Brick III	± 3	±0.32	± 5	±5.88	± 4	±0.15	6	2.6	95	98.16
Brick IV	± 2	±0.32	± 4	±5.88	± 3	±0.15	4	2.6	130	98.16
Brick V	± 1	±0.32	± 3	±5.88	± 2	±0.15	2	2.6	180	98.16
Absorption (not more than 22%)	7.2 %									
Compressive strength per piles / kg/cm^2 (minimum 35 kg/cm^2)	67.17 kg/cm^2									

With respect to the mix with the 1:3:3 proportion (Table 4), in the dimensional variation, either for the 14 and 28 days of life, all the bricks have a type V classification, but there is a risk that there may be variations in their dimensions due to the fact that they are handmade. For the absorption test, the requirements of NTP E.070 were met, which is an absorption of no more than 22%. Nuñez R, (2019) indicates that a greater amount of gravel in the mix reduces absorption. In the warping test, the classification is Brick type IV and type V for 14 and 28 days of life, respectively. These results have not been constant; however, the variation has not been so high. For the mechanical property, according to the compression test per masonry unit, the bricks were classified as type I. This can be deduced from the fact that by adding coarser aggregate (crushed glass), the cement is not in adequate proportion to the cement, as it is no longer sufficient to bind all the aggregates together and as a consequence the bricks were weak. In addition, the pile compression test indicated that the results do not comply with the minimum required in NTP E.070, which is 35kg/cm^2.

Table 4: Compilation of the results for the mixture with the proportion 1:3:3

Type	14 days of life									
	Variation of the dimension (maximum in percent)						Warpage	Obtained	Compressive strength per unit / kg/cm^2	Obtained
	More than 150 mm	Obtained	Up to 100 mm	Obtained	Up to 150 mm	Obtained				
Brick I	± 4	±0.45	± 8	±1.18	± 6	±0.77	10	2.7	50	35.54
Brick II	± 4	-0.45	± 7	±1.18	± 6	±0.77	8	2.7	70	35.54
Brick III	± 3	-0.45	± 5	±1.18	± 4	±0.77	6	2.7	95	35.54
Brick IV	± 2	-0.45	± 4	±1.18	± 3	±0.77	4	2.7	130	35.54
Brick V	± 1	-0.45	± 3	±1.18	± 2	±0.77	2	2.7	180	35.54
Absorption (not more than 22%)	6.9 %									
Compressive strength per piles / kg/cm^2 (minimum 35 kg/cm^2)	32.89 kg/cm^2									
Type	**28 days of life**									
	Variation of the dimension (maximum in percent)						**Warpage**	Obtained	**Compressive strength per unit / kg/cm^2**	Obtained
	More than 150 mm	Obtained	**Up to 100 mm**	Obtained	**Up to 150 mm**	Obtained				
Brick I	± 4	±0.68	± 8	±0.94	± 6	±1.15	10	1.5	50	21.62
Brick II	± 4	±0.68	± 7	±0.94	± 6	±1.15	8	1.5	70	21.62
Brick III	± 3	±0.68	± 5	±0.94	± 4	±1.15	6	1.5	95	21.62
Brick IV	± 2	±0.68	± 4	±0.94	± 3	±1.15	4	1.5	130	21.62
Brick V	± 1	±0.68	± 3	±0.94	± 2	±1.15	2	1.5	180	21.62
Absorption (not more than 22%)	7.2 %									
Compressive strength per piles / kg/cm^2 (minimum 35 kg/cm^2)	24.69 kg/cm^2									

4. Conclusions

The production of artisan bricks from recycled glass proved favorable and can be a complete substitute for the coarse aggregate (gravel) used for the production of conventional bricks. Both mixtures with the proportions 1:3:2 and 1:3:3:3 for the constituents cement/coarse sand/crushed glass behaved well, being the mixture with the proportion 1:3:2 the most suitable, being classified as Type II and the bricks with proportion 1:3:3 does not classify, because they are not within the resistance parameters according to the Peruvian Technical Standard E.070 Masonry for structural purposes. In this way, the use of glass waste is an environmentally sustainable solution that allows the population to contribute to a low-cost brick construction activity.

Acknowledgments

To the César Vallejo University for the academic support and providing the necessary tools to carry out the research and elaboration of this article.

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