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Experimental investigation of the use of crushed clay brick on the properties of sustainable mortar

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Abstract

Globally, millions of tons of construction waste are generated annually, primarily due to the booming construction sector. Among this waste, brick residues are the most prominent. This research aimed to study the properties of mortar with the partial substitution of fine aggregate by brick residues. An experimental methodology was used, involving mortar samples with 10%, 20%, 30%, and 40% brick residue content. These samples were subjected to both mortar and masonry tests. The results indicated that the mortar sample with 10% brick residue performed best. Compared to conventional mortar, this sample showed a 1.58% increase in compressive strength, a 3.99% increase in flexural strength, and a 15.61% increase in tensile strength in mortar tests. In masonry tests, the same sample demonstrated a 12.19% increase in compressive strength in prisms, a 33.20% increase in bond strength, and a 3.82% increase in diagonal compressive strength. In conclusion, substituting fine aggregate with up to 10% brick residues is feasible and optimally improves the mechanical properties of mortar.

Keywords

Mortar, Brick waste, Tensile, Flexural, Compressive

1. Introduction

The manufacture of mortar has presented a great environmental impact due to the excessive extraction of raw materials, which is linked to the increase of temperatures on the planet (Lam, et al., 2021), at the same time, the development of new construction materials has generated an increase in waste, producing between 1.46 to 1.92 tons annually, being part of the environmental problems, because these construction materials are not biodegradable (Nasr, et al., 2020). Due to environmental pollution, construction industries are continuously looking for new alternative materials that are commonly selected from waste for sustainable development in the manufacture of mortars (Srivastava & Singh, 2020), in the same way, being able to reduce the use of natural resources ensures a sustainable solution to employ such waste (Samadi, y otros, 2020).

The use of waste materials in an optimal way contributes to the control of the extraction of natural resources (Ma, Shen, Wang, & Wu, 2022), given that if there is no management, there would be great ecological impacts due to the overexploitation of raw materials (Selvaranjan, et al., 2021), which is why the search for sustainability in construction not only reduces the emission of toxic gases into the environment, but also aims to rescue natural resources (Zhang, et al., 2020).

Due to the development of urban areas, an accumulation of clay brick waste is generated, which is equivalent to 54% of construction waste (Zhu & Zhu, 2020); therefore, such waste represents a good alternative for reuse to be used in the manufacture of mortar in an efficient manner (Joudah, et al., 2021). One of the qualities of reusing brick waste in the mortar mixture is to reduce the unfavorable effects on the environment (Mansoor, et al., 2022). In this aspect, the use of brick dust and crushed brick as a replacement of binder and stone aggregates for concrete and mortar mixes is very important in order to generate environmentally friendly solutions, reducing the overexploitation of natural resources (Pachta, et al., 2021).

One of the principles of the circular economy is to seek to restore and rebuild the cycle of materials, i.e., to preserve their value by reducing waste generation through reuse (Salmenperä, et al., 2021). Therefore, the reuse of bricks from waste has a high potential from an environmental point of view, since reuse contributes with improving material flows, generating changes in the circular economy model, considering that these wastes can be reused as a substitute for aggregates or cement (Fořt & Černý, 2020). In addition, waste reuse is a step towards a circular economy and can avoid the excessive use of natural resources (Singh & Chandel, 2022).

The annual world production of bricks is estimated at 1.83 billion on the planet (Bhairappanavar, et al., 2021); given that they are elements that were first used about seven thousand years ago, given their qualities such as durability and resistance to weathering, due to their clay mineralogical composition (Huarachi, et al., 2020).

The use of clay residues as aggregate not only provides environmental benefits, but also provides mortar strength (Nasr, et al., 2020), so its use as fine aggregate contributes with the improvement of mechanical properties and setting of mortar (Liu, et al., 2020). But the quality of bricks is related to the production method, drying and firing processes, which effects on the final properties of the product, such as compressive strength, tensile strength, wear resistance, impact resistance and water absorption (Reis, et al., 2020).

A large amount of waste in Peru is generated in illegal landfills or solid waste collection sites (Pérez, et al., 2022). Likewise, environmental damage is not considered, so there is a great need to establish recycling models to protect the ecosystem and reduce quarrying (Muñoz-Pérez, et al., 2021).

Regarding the compressive strength of the mortar, we have Liu et al., (2020), expressed that the strength of the mortar with 30% brick residue (BR) obtained a greater increase exceeding the standard mortar by 14.95%. Likewise, Xu et al, (2022) obtained a higher strength at 28 days of curing with 30% of BR, obtaining an increase of 13.29% with respect to the standard mortar, revealing that this increase is due to the pozzolanic properties of BR. On the other hand, Zhao et al, (2022), reported that the compressive strength decreased progressively with the incorporation of BR in the mortar up to a curing age of 28 days, presenting within the experimental samples the lowest decrease of 3.30% in the mortar with 25% BR.

Regarding the flexural strength of the mortar, Huang et al (2021), verified that the flexural strength of the mortar increases with the curing period, having with the dosage of 100% of BR an increase of 11.3% in relation to the standard mortar. In the same way, Campinho et al (2023), showed that with the dosage of 10% of BR the flexural strength increased by 29.37% with respect to the standard mortar. On the other hand, Raini et al., (2020) mentioned that the BR content in the mortar has an unfavorable influence on the flexural strength; thus, with 15% BR it remains approximately the same as the standard mortar, showing a slight decrease rate of 2.94%.

In relation to the tensile strength of the mortar Xu et al., (2022), mentioned that the mortar with 30% BR presented a higher tensile strength achieving a maximum increase of 9.88% respectively, due to the pozzolanic reaction generated by the BR in the mortar. Likewise, Qi et al, (2023), exposed the mortar with high concentrations of BR showed higher strengths compared to the standard mortar, achieving with 30% of crushed brick an increase of 8.74%, so it was conjectured that the BR is a pozzolanic material that is composed of silicate oxide which reacts with the calcium hydroxide of the cement forming a mortar with higher strength.

Regarding the properties of mortar in masonry, Poongodi and Murthi, (2022), observed that its compressive strength in masonry prisms increased with the substitution of 10% of the coarse sand by BR, having with a design of 1:6 and 1:8 an increase of 2% and 1.19%, respectively. Likewise, Murthi et al., (2020), showed that BR in mortar improves the mechanical behavior in masonry, having with a dosage of 15% BR a maximum increase of 4.29% in the compressive strength in prisms and with 10% BR an increase of 12.38% for the shear bond strength.

From the information search, it can be inferred that the use of BR is due to the imperative advance of the development of the construction sector, which has generated a great environmental impact due to the use of non-renewable raw materials, leading to the existence of studies on the use of brick waste in mortar and concrete. The information gap is due to the fact that only the properties of mortar with BR in a late setting stage have been studied, in addition to not covering the properties in masonry with mortar. Consequently, there is a need to expand the knowledge on the behavior of mortar in different setting periods as well as in different structural properties. The purpose of the research was to study the properties of mortar with the substitution of fine aggregate by BR in dosages of 10%, 20%, 30% and 40% with respect to the weight of fine aggregate.

2. Materials and Methods

2.1 Materials

The coarse sand was extracted from the Victoria quarry located in the district of Patapo, Peru, and was taken to the laboratory for tests such as grain size ASTM C136 (2006), unit weight ASTM C29 (1997), moisture content ASTM C566 (2019), specific weight and absorption ASTM C128 (2022), to determine its physical properties in order to determine if it complied with the regulations, as shown in Table 1.

Table 1. Fine aggregate properties

Properties	Data	Standard ASTM
Fineness modulus	2.62	ASTM C136 (2006)
Moisture Content (%)	1.57	ASTM C 566 (2019)
Wet loose unit weight (kg/m^3)	1351.91	ASTM C29 (1997)
Dry loose unit weight (kg/m^3)	1331.03	
Wet compacted unit weight (kg/m^3)	1544.71	
Dry compacted unit weight (kg/m^3)	1520.86	
Specific gravity (gm/cm^3)	2.53	ASTM C128 (2022)
Absorption (%)	1.30	

Note: Own elaboration

Type I Portland cement was used, complying with the requirements of ASTM C150 (2012), with a specific weight of 3.62 gm/cm3, air content of 6.0%, retained air of 45 µm 8.40% and loss on ignition of 2.47%.

Brick waste can be obtained from its production process, presenting an optimal potential to be used in crushed form as a replacement for stone aggregate (Muñoz-Pérez, et al., 2021). Likewise, such waste is also usually found in demolition debris and brick kilns because they produce high accumulations of construction material waste (Moreno, et al., 2019). The brick waste used for the research was crushed and sieved through mesh No. 4 (4.75 mm), eliminating any retained material, on the other hand, a sample was taken from the passing material and its chemical composition was studied, obtaining the results shown in Table 2.

2.2 Mix design

In this study, a 1:4 design was established for the preparation of the standard mortar and at the same time for the preparation of the mortar with the substitution of coarse sand for brick residues. A codification was assigned for each dosage being MP-0 for the conventional mortar, likewise, for the mortar with brick residues at 10%, 20%, 30% and 40% the codification of MP-1, MP-2, MP-3 and MP-4 was assigned correspondingly, having the following mixture proportions that can be appreciated in Table 3.

Table 2. ICP-OES analysis of brick wastes

Elements (mg/kg)	LCM*	LT
Silver – Ag	0.019	2.65
Aluminum – Al	0.023	4525.69
Arsenic – As	0.005	0.00435
Boron – B	0.026	2.965
Barium – Ba	0.004	159.25
Beryllium – Be	0.003	<LCM
Bismuth – Bi	0.016	<LCM
Calcium – Ca	0.124	25029.26
Cadmium – Cd	0.002	0.298
Cerium – Ce	0.004	4.12
Cobalt – Co	0.002	1.62
Chromium - Cr	0.003	1.697
Copper – Cu	0.018	80.256
Iron – Fe	0.023	14852
Potassium – K	0.051	0.0258
Lithium – Li	0.005	1.298
Magnesium – Mg	0.019	1525.25
Manganese - Mn	0.003	109.26
Molybdenum – Mo	0.002	19.895
Sodium – Na	0.026	2.596
Nickel – Ni	0.006	0.64
Phosphorus - P	0.024	19.60
Lead – Pb	0.004	0.269
Sulfur – S	0.091	19.66
Antimony – Sb	0.005	<LCM
Selenium – Se	0.007	<LCM
Silicon – Si	0.104	18598
Tin – Sn	0.007	25.587
Strontium – Sr	0.003	60.258
Titanium – Ti	0.004	0.4446
Thallium – Ti	0.003	<LCM
Uranium – U	0.004	<LCM
Vanadium – V	0.004	0.0859
Zinc – Zn	0.018	0.411
Silicon dioxide – SiO_2	0.222	29256
Mercury – Hg	0.003	<LCM

Note: Own elaboration

Table 3. Ratios of materials for mortar 1:4

Codification	Cement	Sand	BR
MP-0	1	4	0
MP-1	1	3.72	0.28
MP-2	1	3.48	0.52
MP-3	1	3.28	0.72
MP-4	1	3.08	0.92

Note: Own elaboration

2.3 Sample preparation

The sample preparation procedure consisted of pre-weighing the materials to be used according to the mortar mix design to be developed. For this purpose, the cement, coarse sand, brick waste and 2/3 of the water were mixed using a mixer for a period of 1 minute. Then the coarse sand and brick waste were added for mixing again for a period of 30 seconds and finally the remaining water was added and mixed for another 30 seconds or until the homogeneity of the mixture was obtained.

2.4 Method

For the present study, an experimental methodology was adopted based on ASTM standards for the execution of the relevant tests, in order to analyze the mortar mixture with the best performance, a process that can be seen in the flow chart in Figure 1 was followed.

Compressive strength of mortar test

This test was carried out according to ASTM C349 (2018), where it is indicated that the compressive strength of the mortar is determined by making 50 mm cubes on each side, having 3 samples for a 1:4 design with the substitution of sand for brick waste at 10%, 20%, 30% and 40%, tested at 7, 14 and 28 days.

Flexural strength of mortar test

The flexural capacity was determined according to ASTM C348 (2021), making mortar bars with proportions of 160 mm x 40 mm x 40 mm, in the same way, having 3 samples for a 1:4 design with the substitution of sand for brick waste in 10%, 20%, 30% and 40%, tested at 7, 14 and 28 days.

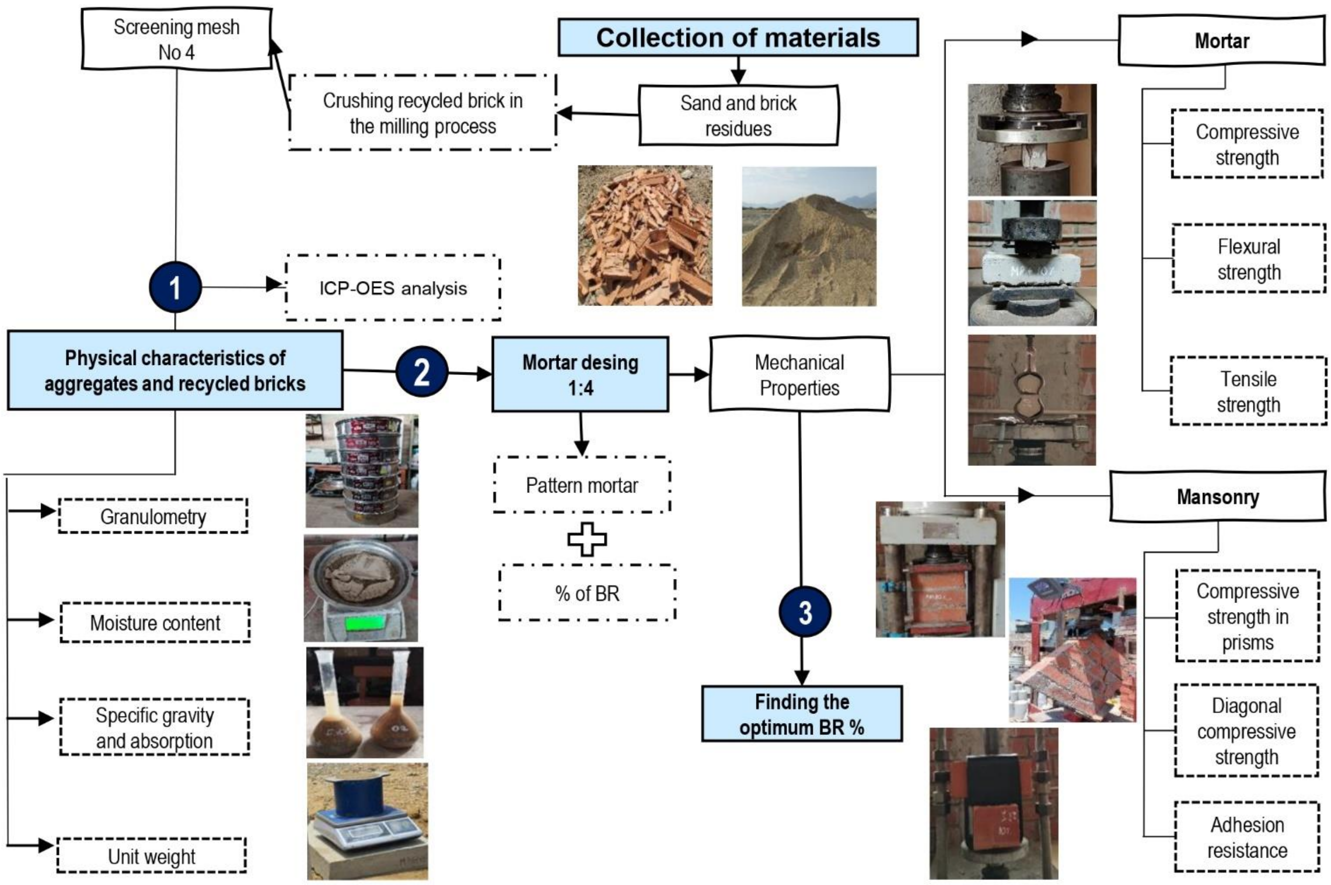

Fig. 1 Research flowchart

Tensile strength of mortar test

The test to establish the tensile capacity was carried out according to ASTM C307 (2018), which indicates that the mold for mortar briquettes should have a thickness of 1 inch (25.4 mm), tolerating different variations according to the time of use. For this test, 3 samples were prepared for a mortar design in 1:4 and with the substitution of sand by brick waste in 10%, 20%, 30% and 40%, tested at 7, 14 and 28 days.

Adhesion resistance test

To determine the bond strength of the mortar in masonry units, it was carried out according to ASTM C270 (2019). For this purpose, 3 masonry piles were prepared for a 1:4 design with sand substitution by brick waste at 10%, 20%, 30% and 40%, tested at 7, 14 and 28 days. The test consisted of applying a perpendicular load to the masonry samples lying on the test equipment.

Compressive strength in prisms test

This test was performed according to ASTM C1314 (2021), for which brick prisms were made, each brick having a minimum height of 100 mm. These prisms were cured for 48 hours and then covered with bags and kept in an area at a temperature of 24 °C ± 8 °C. Also, two days before the breakage the bags were removed. To determine the compressive strength in prisms, 3 samples were prepared for a 1:4 design with the substitution of sand for brick waste at 10%, 20%, 30% and 40%, being tested at 7, 14 and 28 days.

Diagonal compressive strength test

Based on the requirements of ASTM E519 (2007), the walls were formed by 6 courses by 2.5 of clay bricks, with 1.5 cm thick joints, resulting in walls of 60 cm x 60 cm. The walls were tested on 7, 14 and 28 days.

3. Results and Discussions

3.1 Analysis of the compressive strength of mortar

In Figure 2, the compressive strength is shown, where it can be deduced that with a higher BR content, the compressive strength decreases obtaining the highest value at 28 days with MP-1, achieving an increase of 1.58% with respect to MP-0. This increase in compressive strength is also presented in the research of Liu et al, (2020), Xu et al., (2022) and Zhao et al., (2022). However, it differs in the optimum dosage since for Liu et al., (2020) that with 30% BR obtained an increase of 14.95%. Similarly for Xu et al., (2022) its optimum dosage was 30% BR achieving an increase of 13.29%. On the other hand, Zhao et al., (2022) obtained with 25% BR an increase of 3.30%.

3.2 Analysis of the flexural strength of mortar

The findings shown in Figure 3 indicate that the flexural strength obtained is congruent with the compressive strength because it obtained its maximum value with the same dosage of BR, with MP-10 having a better performance, reaching an increase of 3.99%. This same trend was found in the research of Campinho et al, (2023), that with a dosage of 10% BR achieved an increase of 29.37%. Huang et al. (2021) found that, while there was an 11.30% increase in flexural strength, the optimal dosage was 15% BR. On the other hand, according to the research of Raini et al., (2020), the trend is opposed since the flexural strength with all the BR dosages was lower than the conventional mortar, presenting with 15% BR, a slight decrease of 2.94%.

3.3 Analysis of the tensile strength of mortar

It is shown in Figure 4, that the tensile strength of the mortar with the MP-10 dosage obtained the highest value with an increase of 15.61% at 28 days compared to the conventional mortar sample. This result differs with that shown by Xu et al (2022) and Qi et al, (2023), having as optimum dosage that of 30% BR, obtaining an increase of 9.88% and 8.74% respectively, reaching the deduction that the crushed brick is a pozzolanic material that is composed of silicate oxide which reacts with the calcium hydroxide of the cement forming a mortar with a higher resistance.

3.4 Analysis of adhesion strength

The bond strength evidenced in Figure 5, showed the same behavior as the other tests of mortar in masonry reaching its maximum peak with the dosage of MP-1, and then gradually reducing its strength with higher dosages such as MP-2, MP-3 and MP-4. This behavior was recorded in the same way in all the evaluated time periods, so that with the dosage of MP-1 the mortar achieved an increase of 33. 20% at 28 days with respect to conventional mortar. This trend is corroborated with the research of Murthi et al, (2020), which presented as a result a 12.38% increase in shear bond strength at 10% BR dosage. This can be attributed to the pore-filling property of BR which helps the cement to hydrate, optimizing its strength capacity.

3.5 Analysis of compressive strength in prisms

The results showed that the compressive strength in prisms increased up to the MP-1 dosage and then tends to decrease with higher dosages such as MP-2, MP-3 and MP-4, so the MP-1 mortar obtained a better performance, achieving an increase in its value of 12.19% at 28 days with respect to the conventional mortar sample (MP-0), as shown in Figure 6. Structural reinforcement and mixture optimization are two key approaches to increase the compressive strength in a prism with brick waste. These results are confirmed by the research of Poongodi and Murthi (2022), due to the act that with 10% coarse sand substitution by BR, it achieved the maximum resistance with an increase with respect to the standard mortar of 2% and 19% with a design of 1:6 and 1:8.

3.6 Analysis of diagonal compressive strength

As in the masonry tests previously presented, the diagonal compressive strength shown in Figure 7, had the same trend being congruent with the results, having for the conventional mortar with a 1:4 design a value of 1.57 kg/cm2 at 28 days, while with the MP-1 mortar sample a strength of 1.63 kg/cm2 was achieved, representing an increase of 3.82%. This is related to the results obtained by Poongodi and Murthi (2022) and Murthi et al., (2020) who achieved a better performance in masonry with a dosage of 10% BR, maintaining the same trend.

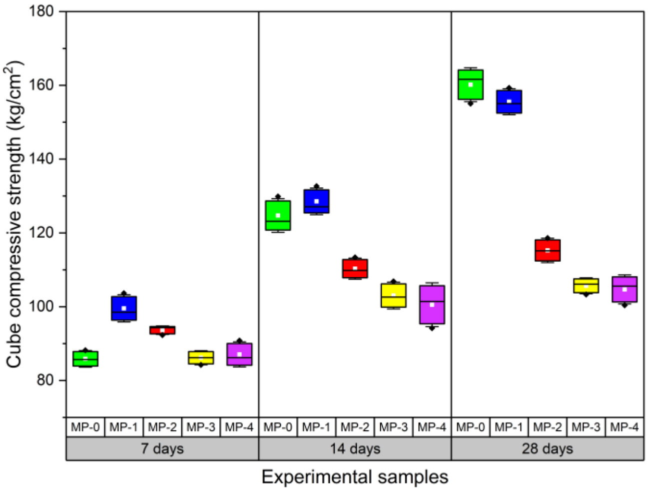

Fig. 2 Boxplot of compressive strength of mortar

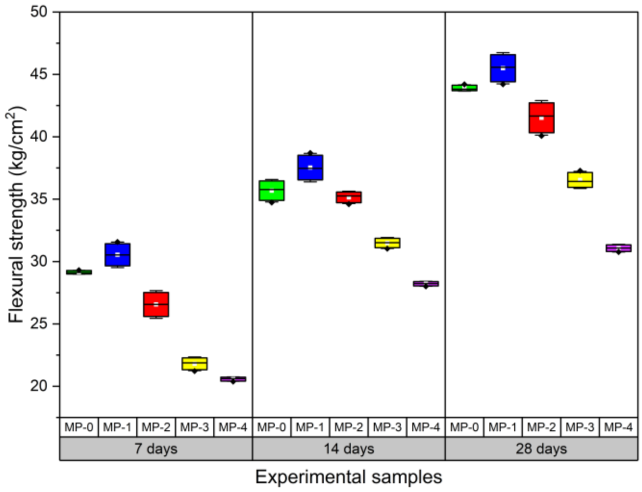

Fig. 3 Boxplot of flexural strength of mortar

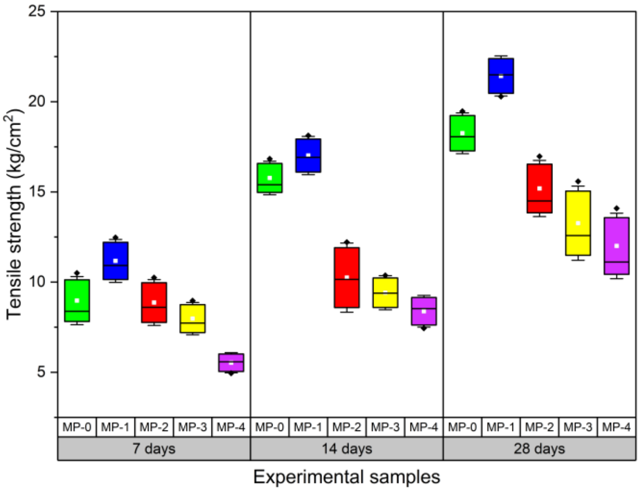

Fig. 4 Boxplot of tensile strength of mortar

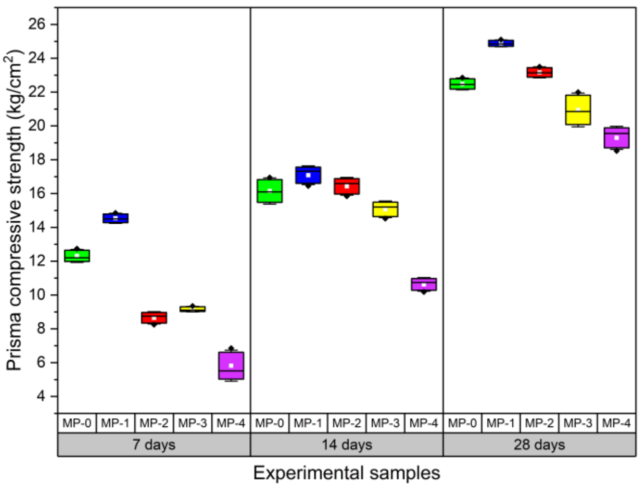

Fig. 5 Boxplot of adhesion resistance

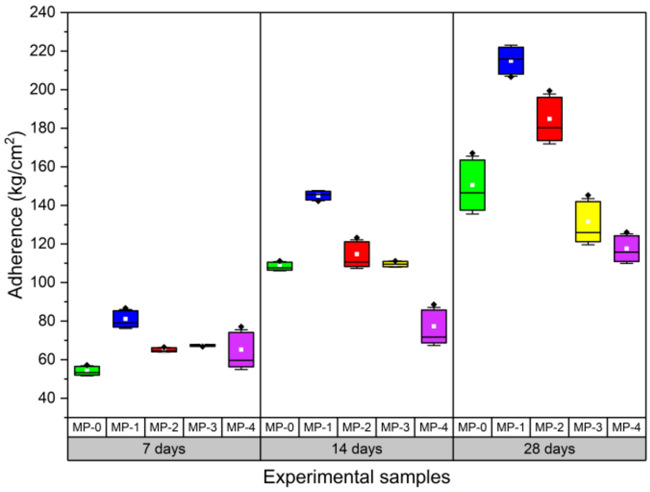

Fig. 6 Boxplot of compressive strength in prisms

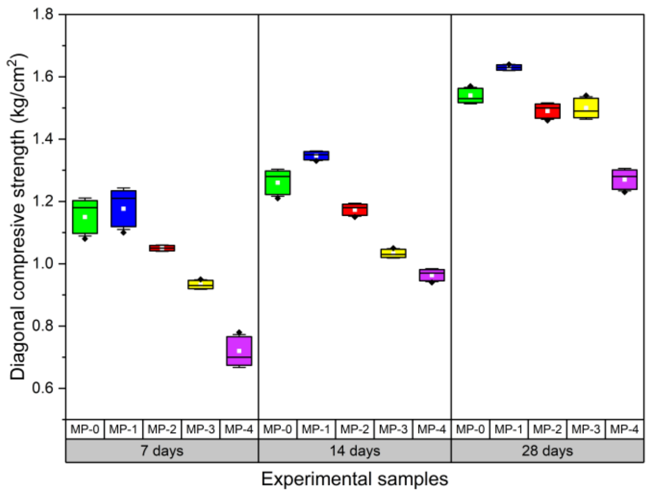

Fig. 7 Boxplot of diagonal compressive strength

4. Conclusions

Significant advances in the understanding of mortar behavior have been developed in recent years, however, the main findings with the addition of brick waste are highlighted. The conclusions derived from the present investigation can be drawn as follows:

1. With 10% brick residues as cubed compressive strength, tensile strength and flexural strength achieved an increase of 1.58%, 3.99% and 15.61% at 28 days, respectively.
2. Regarding prism compressive strength, bond strength and diagonal compressive strength, they achieved an increase of 12.19%, 33.20% and 3.82%, respectively at 28 days with the addition of 10% BR.
3. It is observed that the use of brick residues generates a better adherence of the mortar to the masonry unit, thus influencing a better distribution of stresses under compressive and tensile stresses.

It was possible to demonstrate the benefits of replacing fine aggregate with brick waste by up to 10%, improving its mechanical properties in an optimum manner, contributing new knowledge on the tests analyzed. The reuse of waste materials can be used in the preparation of mortars for non-load-bearing masonry structures.

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