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Evaluating the Use of Recycled Brick Powder as a Partial Replacement for Portland Cement in Concrete

Evaluación del uso del polvo reciclado de ladrillo como reemplazo parcial al cemento Portland en el hormigón

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ABSTRACT

Portland cement is one of the most used construction materials. However, its production represents between 5 and 7% of the total CO_2 emissions. On the other hand, during construction and demolition activities, different wastes are produced, including recycled brick powder (RBP), whose potential as a supplementary cementitious material (SCM) has been demonstrated in the literature. This research aims to evaluate RBP as a partial replacement for Portland cement in concrete. 5 to 10% of Portland cement was replaced with RBP in two strength designs (20 and 25 MPa) in order to propose concretes that meet the requirements for use in construction. Tests involving slump, compressive strength, tensile strength by diametrical compression, absorption, density, and void content were performed. The results show that a 5% RBP replacement does not affect workability in concrete mixes, as it maintains their mechanical resistance and slightly improves their physical properties. On the other hand, 10% RBP replacements adversely affect workability and reduce tensile strength. These results are attributed to pozzolanic activity and the physical effect caused by RBP, whose performance may be improved by reducing RBP particles and increasing their specific surface area (SSA). Using RBP as a replacement for Portland cement to produce concrete is a viable alternative with a sustainable approach.

Keywords: workability, mechanical properties, physical properties, sustainability

RESUMEN

El cemento Portland es uno de los materiales de construcción más utilizados. Sin embargo, su producción representa entre el 5 y el 7 % de las emisiones totales de CO_2. Por otro lado, durante las actividades de construcción y demolición, se producen diferentes residuos, entre ellos el polvo de ladrillo reciclado (PLR), cuyo potencial como material cementante suplementario (MCS) ha sido demostrado en la literatura. El objetivo de la presente investigación es evaluar el PLR como reemplazo parcial del cemento Portland en el hormigón. Se sustituyó 5 y 10% de cemento Portland por PLR para dos resistencias de diseño (20 y 25 MPa), a fin de proponer concretos que cumplan con los requerimientos para ser utilizados en la construcción. Se realizaron ensayos de asentamiento, resistencia a la compresión, resistencia a la tracción por compresión diametral, absorción, densidad y contenido de vacíos. Los resultados muestran que la sustitución del 5% de PLR no afecta la trabajabilidad de las mezclas, pues mantiene las resistencias mecánicas y mejora levemente las propiedades físicas. Por otro lado, las sustituciones del 10% de PLR afectan negativamente la trabajabilidad y reducen la resistencia a la tracción. Estos resultados se atribuyen a la actividad puzolánica y al efecto físico del PLR, cuyo desempeño puede ser mejorado si se reducen las partículas de PLR y se incrementa el área superficial específica (ASE). El uso de PLR como reemplazo del cemento Portland para la elaboración de hormigón es una alternativa viable con enfoque sostenible.

Palabras clave: trabajabilidad, propiedades mecánicas, propiedades físicas, sostenibilidad

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Introduction

Portland cement is one of the most used materials in the construction industry, especially for concrete production (Habert *et al.*, 2020). Due to high demand, particularly from developing countries, Portland cement production has been increasing, and an increasing trend is projected for the coming years (UN Environment *et al.*, 2018). However, manufacturing Portland cement requires a high consumption of natural resources and energy, so it constitutes an important source of carbon dioxide (CO_2) emissions, approximately 5-7% of the total anthropogenic CO_2 emissions (Singh and Middendorf, 2020; Sousa and Bogas 2021). This is due to limestone decomposition ($CaCO_3 \rightarrow CaO + CO_2$) at high temperatures (~1 450 °C) in order to produce clinker, Portland cement's main component. This process releases CO_2 and consumes significant amounts of fossil fuel (Gao *et al.*, 2021; Arif *et al.*, 2021). To reduce the environmental impacts of using Portland cement, a partial replacement with

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supplementary cementitious materials (SCMs) has been proposed (Jiang *et al.*, 2020; Rocha *et al.*, 2022; Panesar and Zhang, 2020).

Using SCMs in concrete is a widely spread strategy to reduce CO_2 emissions which may improve material durability and constitutes a sustainable approach in the construction industry depending on the characteristics and content of SCMs (Panesar and Zhang, 2020). However, the availability of these materials hinders their implementation (Juenger and Siddique, 2015). In this sense, using local waste such as municipal solid waste (MSW) and agro-industrial waste as SCMs has been proposed (Thomas *et al.*, 2021; Tripathy and Acharya, 2022), as well as construction and demolition waste (CDW) (Tang *et al.*, 2020; Likes *et al.*, 2022), among others (Juenger *et al.*, 2019; Jiang *et al.*, 2022; Zhou *et al.*, 2021).

On the other hand, a rapid population growth has influenced the increase in construction activities, thus generating more CDW, *i.e.*, waste made up of sand, gravel, concrete, mortar, bricks, and glass, among others (Wong *et al.*, 2018; Vieira *et al.*, 2020). Recent studies have repurposed CDW as recycled aggregates to produce concrete and mortar, demonstrating its technical and environmental feasibility (Da Silva *et al.*, 2022; Borges *et al.*, 2023). Da Silva *et al.* (2023) pointed out that the use of CDW as a recycled aggregate, in conjunction with fly ash (FA) and hydrated lime (HL), has a synergistic effect that could enhance the mechanical properties and durability of concrete. In this sense, Da Silva and Andrade (2022) argued that the use of both CWD and SCMs such as FA, metakaolin (MK), and rice husk ash (RHA), among others, could provide economic, environmental, and energy benefits in the production of new cement-based materials.

Brick is quite widely used in construction, followed only by concrete (Adamson *et al.*, 2015). Several studies have proposed the utilization of brick residue as a recycled aggregate in the construction industry (Mohammed *et al.*, 2015; Ge *et al.*, 2021; Nguyen *et al.*, 2023). However, in order to provide a sustainable solution for increasing cement production and CDW generation, the use of recycled brick powder (RBP) has been studied in recent years (He *et al.*, 2021). Several studies have shown that RBP is a pozzolanic material given its high SiO_2 and Al_2O_3 contents, in addition to the amorphous compounds formed during the brick-making process (Reig *et al.*, 2013; Ortega *et al.*, 2018). On the other hand, Luo *et al.* (2022) not only highlighted the chemical characteristics of RBP, but also its physical effects, such as filling and nucleation.

Arif *et al.* (2021) replaced Portland cement with 5 and 10% RPB in order to produce concrete. These authors reported an increase in both workability and mechanical properties, attributing this behavior to the morphology and pozzolanic activity of RBP particles. Liu *et al.* (2020) also found that substituting Portland cement with 10% RBP may improve mechanical strength in mortars. Naceri and Hamina (2009) indicated that up to 20% RBP may maintain or improve the compressive strength of concrete and mortar, due to the amorphous SiO_2 content that promotes pozzolanic reaction, thus forming hydrated calcium silicate (C-S-H). Likes *et al.* (2022) indicated that the use of 20% RBP resulted in a strength activity index (SAI) of 98% for concrete after 28 days, as well as an improvement in durability when compared to the reference.

Although there is literature on the use of RBP as a partial replacement for Portland cement, each study has considered different material characteristics. In order to propose RBP as an application-focused SCM, this study intends to replace Portland cement with RBP while considering two concrete strength designs (20 and 25 MPa) and local materials from the city of Cochabamba, Bolivia. Thus, this study intends to evaluate workability and both physical and mechanical concrete properties, replacing Portland cement with 5 and 10% RBP. The substitution percentages were selected with the purpose of proposing concretes with RBP that have the same physical-mechanical properties as conventional concrete, thus providing an alternative for the reuse of RBP in concrete for structural purposes.

Materials and methods

Materials

For this research, RBP was obtained from a demolition site in Cochabamba, Bolivia. The RBP went through a sieving process using a fraction-exceeding #100 sieve (150 μm). IP 40 cement was used, corresponding to Portland modified with pozzolan, according to the ASTM C595 standard (American Society for Testing and Materials, 2021a).

The chemical composition for both the RBP and the IP 40 cement was determined via X-ray fluorescence spectrometry (XRF). The results are presented in Table 1. Regarding the RBP, the sum of chemical components $SiO_2+Al_2O_3+Fe_2O_3$ was higher than 70%, meeting the requirements to be classified as a pozzolanic material in accordance with ASTM C618 (American Society for Testing and Materials, 2022).

Table 1. Chemical composition for RBP and IP 40 cement (in %)

Chemical compounds	IP 40 cement	RBP
CaO	70,69	6,90
SiO_2	12,95	44,22
Fe_2O_3	5,04	26,06
Al_2O_3	4,61	8,37
SO_3	3,11	6,02
K_2O	0,45	4,14
TiO_2	0,34	1,74
MnO	0,24	0,13
SrO	0,56	0,05
ZrO_2	-	0,05
LOI	2,01	2,32

Source: Authors

The physical properties of both the RBP and the IP 40 cement were determined. Their particle size distribution was determined via laser diffraction, their density by means of helium gas pycnometry, and their specific surface area (SSA) according to the ASTM C204 (American Society for Testing and Materials, 2019). Figure 1 and Table 2 present the materials' particle size distribution and a summary of their physical properties, respectively.

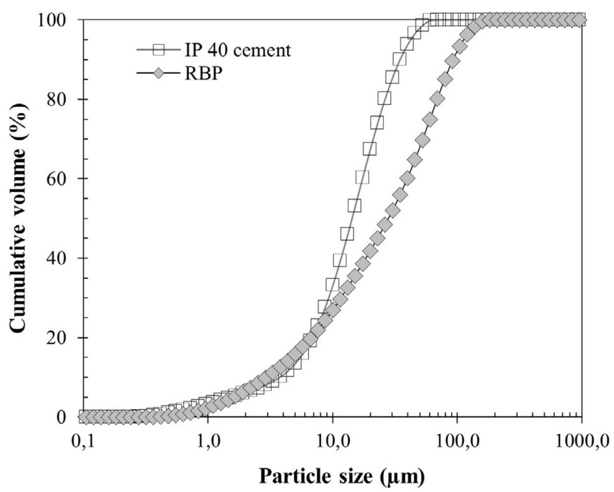


Figure 1. Particle size distribution of the RBP and the IP 40 cement
Source: Authors

Table 2. Physical properties of the RBP and the IP 40 cement

Parameter	RBP	IP 40 Cement
D10 (µm)	2,93	3,75
D50 (µm)	27,99	14,26
D90 (µm)	92,40	34,60
Specific gravity (g/cm³)	2,69	3,07
Specific surface area (cm²/g)	3 443,90	3 642,51

Source: Authors

The RBP's mineral composition was determined via X-ray diffraction (XRD). The XRD pattern for the RBP is presented in Figure 2, where quartz is the largest crystalline phase, followed by other compounds: hematite, ilite, albite, and gypsum – the latter due to possible contamination at the demolition site. The proportion corresponding to the RBP's amorphous phase is 60,7%, as determined by refinement according to the Rietveld method.

The granulometric distribution of coarse and fine aggregate was determined by following the ASTM C136 standard (American Society for Testing and Materials, 2015a) (Figure 3). The fineness modulus of coarse and fine aggregate was 7,37 and 2,65, respectively, with a maximum aggregate size of 19 mm. Following the ASTM C127 (American Society for Testing and Materials, 2015b) and C128 (American Society for Testing and Materials, 2015c) methods, the relative density of coarse and fine aggregate was determined, obtaining 2,63 and 2,77 g/cm³, respectively.

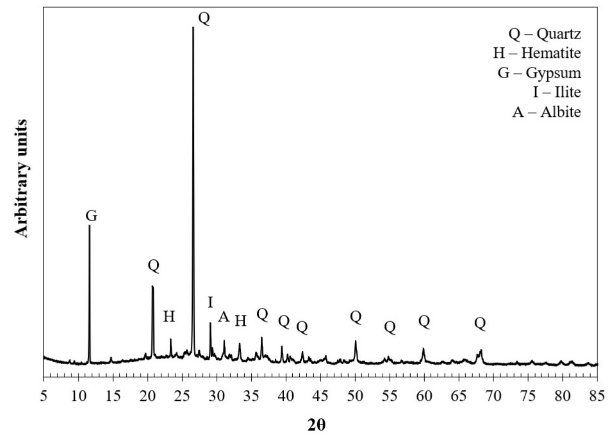


Figure 2. X-ray diffraction pattern of the RBP
Source: Authors

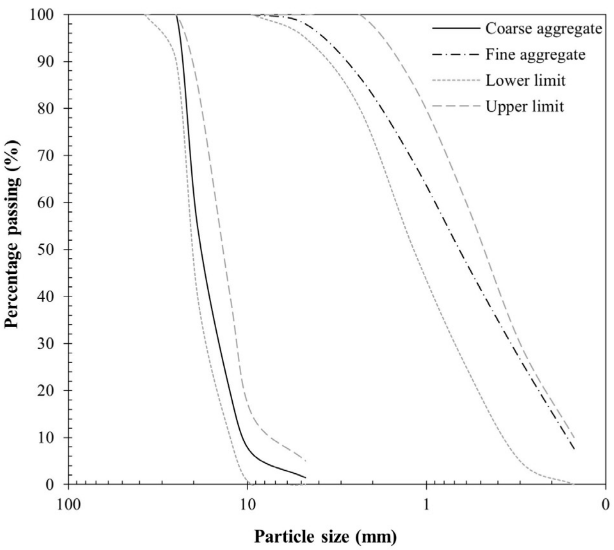


Figure 3. Granulometric distribution of coarse and fine aggregate
Source: Authors

Methods

Definition of mixtures. Two compressive strengths, *i.e.*, 20 (C20) and 25 MPa (C25), were considered since the CBH 87 Bolivian standard establishes them for use in building structures (IBNORCA, 1987). The ACI 211 guidelines (ACI, 1991) were followed as the design mixture method for C20 and C25 concretes. For each design strength, IP 40 cement was replaced with 5 and 10% RBP (by weight). Table 3 summarizes the material amounts for the proposed concretes.

Concrete was prepared in a mechanical mixer, and 10 x 20 cm cylindrical molds were used; the specimens were cured in a humid chamber until the day of their test. The mixing procedure was carried out in accordance with the recommendations of CBH 87 (IBNORCA, 1987). The first half of the water was placed in the mixer, followed by the fine aggregate and binders. The coarse aggregate was then added, and the remaining water was added last. The mixing time was a minimum of 3 minutes.

Table 3. Mix proportions for each concrete strength design

Materials	Mixtures					
	C20			C25		
	Reference (0%)	5% RBP	10% RBP	Reference (0%)	5% RBP	10% RPB
Cement Portland	306,9	291,6	276,2	341,6	324,5	307,4
RBP	0	15,3	30,7	0	17,1	34,2
Water	199,5	199,5	199,5	187,9	187,9	187,9
Sand	903,6	903,6	903,6	1 024,6	1 024,6	1 024,6
Coarse aggregate	1 071,1	1 071,1	1 071,1	1 202,2	1 205.2	1 205.2

Source: Authors

Scanning Electron Microscopy (*SEM*). A microstructural analysis of RBP particle shape was performed by SEM. Hydration products were also detected in concrete mixtures including RBP.

Workability. Workability of the mixtures was evaluated by Abrams's cone slump test, following the UNE-EN 12350-2 standard (Spanish Association for Standardization, 2020). Four measurements were taken per mixture in order to calculate the mean and standard deviation.

Compressive and tensile strength. The compressive and tensile strength of every mixture (by diametrical compression) were determined after 7, 28, and 56 days using ASTM C39 (American Society for Testing and Materials, 2021b) and NBR 7222 (ABNT, 2011), respectively. For both properties, 10 x 20 cm cylindrical molds were used, and four samples for each mixture and age were tested.

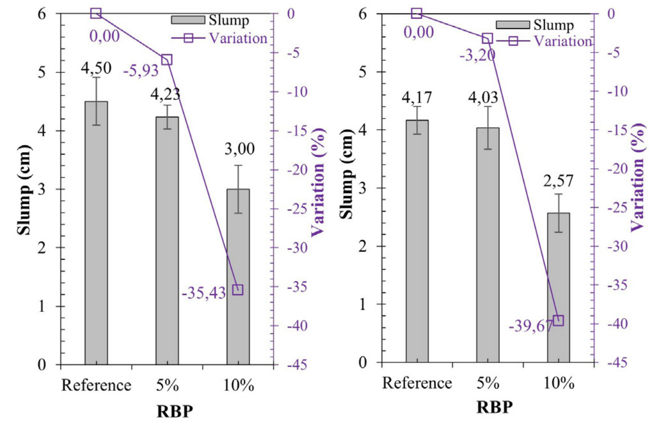
Water absorption, specific mass and void index. Following the ASTM C642 standard (American Society for Testing and Materials, 2021c), water absorption, specific mass, and void index were determined after 28 days. 10 x 20 cm cylindrical molds were used, and four samples were considered for each mixture and physical property.

The data were compared using a one-way analysis of variance (ANOVA) with Tukey's test (p≤0,05).

Results and discussion

Slump test

The slump results for mixtures including RBP are presented in Figure 4. A tendency towards reducing workability for both design resistances was observed. For C20 mixes, the reductions were 5,93 and 35,43% for replacements of 5 and 10% RBP, respectively. Similar results were obtained for the C25 mixes: 3,20 and 39,67% for 5 and 10% RBP.



(a) (b)

Figure 4. Slump for a) C20 and b) C25
Source: Authors

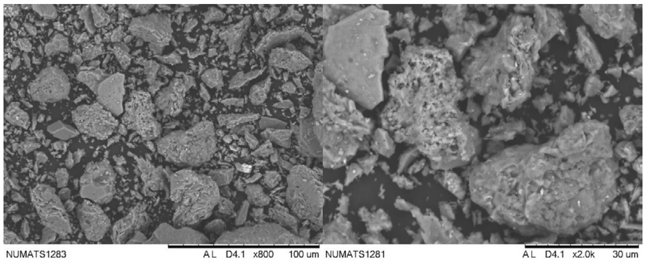
Through the ANOVA, significant differences were found for both C20 (p-value=0,011) and C25 (p-value=0,004). Table 4 presents Tukey's test results. There is no difference between the slump reference and 5% RBP for both C20 and C25, thus confirming that an RBP replacement of up to 5% has no influence on the slump. On the other hand, 10% RBP significantly reduces the slump by more than 35% in both design resistances. Similar results were found by Ge *et al.* (2015). According to them, for low RBP percentages, the workability is similar to the reference, but it is drastically reduced at 20-30% RBP.

Table 4. Tukey's test for the slump

Group 1	Group 2	p-value	
		C20	C25
Reference	5% RBP	0,7427	0,9081
Reference	10% RBP	0,0129	0,0055
5% RBP	10% RBP	0,0302	0,0084

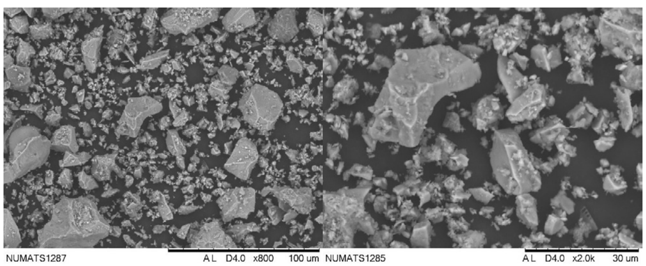
Source: Authors

As the cement replacement with RBP increases, the slump decreases. This behavior is also reported in the literature (Schackow *et al.*, 2015; Luo *et al.*, 2022; Ma *et al.*, 2020a). The workability loss is attributed to irregular RBP particles, thus increasing the water demand and reducing the air content in the mix (Liu *et al.*, 2020; Tang *et al.*, 2020). However, it may be observed that the addition of RBP in low proportions (≤5%) has no influence on the slump. This behavior can be attributed to the fact that RBP (D50) particles are larger than those of cement, in addition to having a lower SSA (Table 2). These characteristics reduce the water demand. However, as shown in Figure 5, RBP particles are porous when compared to IP 40 cement (Figure 6), which could have a negative effect on the workability of the mixes. For 5% RBP, the particle size and the SSA were higher than the RBP porosity, so there were no significant differences. On the other hand, the high slump reduction for 10% RPB may be explained by a) the porosity of the RBP particles, which, for a 10% substitution, had a significant adverse effect on workability; b) the high amount of RBP particles that did not generate an adequate packing, which could entail friction between particles; and c) the shape and rough texture of RBP particles in comparison with IP 40 cement.



(a) (b)

Figure 5. SEM images of RBP at different magnifications: a) 800 and b) 2k
Source: Authors



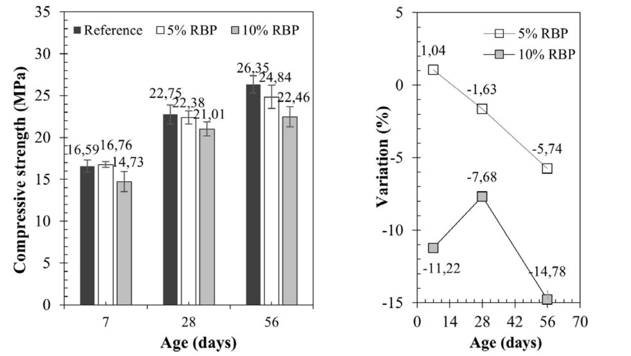
(a) (b)

Figure 6. SEM images of IP 40 cement at different magnifications: a) 800 and b) 2k
Source: Authors

Schackow *et al.* (2015), Ma *et al.* (2020a), and He *et al.* (2021) point out that RBP particles reduce the workability of cement-based materials due to their irregular microstructure and size, thus increasing the water demand. Luo *et al.* (2022) indicate that workability reductions are also related to the SSA of RBP, which, in this case, is similar to that of IP 40 cement (Table 2). Adding more water content and/or using superplasticizers to offset this effect is recommended. Zhao *et al.* (2020) point out that, if the RBP particle size is reduced, the microstructure becomes regular and non-angular, thus generating a lubricating effect and compensating for the water requirements.

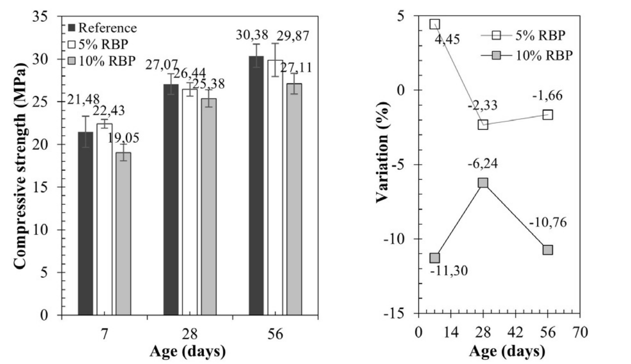
Compressive strength

The compressive strength results are presented in Figures 7 and 8 for C20 and C25, respectively. Regarding C20, a reduction trend is observed when adding RBP. 5% RBP shows the smallest negative variation, which is even higher than the reference for 7 days, *i.e.*, 1,04%. 10% RBP exhibits a greater reduction in compressive strength, with the maximum value being 14,78% for 56 days. However, through the ANOVA, it can be concluded that the compressive strength means are statistically the same for every period, *i.e.*, for 7 (p-value=0,356), 28 (p-value=0,133), and 56 days (p-value=0,054), thus indicating that an addition of 5 and 10% RBP does not have a significant influence on compressive strength. It is important to emphasize that, in all cases, the p-value is greater than 0,05, meaning that the mixtures have statistically equal means. Therefore, the addition of 5 and 10% RBP would not affect this property for C20 concrete.



(a) (b)

Figure 7. a) Compressive strength for C20. b) Compressive strength variation regarding the reference.
Source: Authors



(a) (b)

Figure 8. a) Compressive strength for C25. b) Compressive strength variation regarding the reference.
Source: Authors

Likewise, every C25 mix exhibits a negative trend when replacing IP 40 cement with RBP. For 5% RBP, an increase in compressive strength after 7 days (4,45%) is observed. Therefore, later ages exhibit smaller reductions (<2,5%). In the case of 10% RBP, the reductions are greater, with a maximum negative variation of 11,30% for 7 days. Despite a tendency towards reducing compressive strength, the ANOVA confirms that there are no significant differences between the means of mixtures including RBP and the reference, considering stages of 7 (p-value=0,080), 28 (p-value=0,314), and 56 days (p-value=0,150). The p-values for C25 concrete were greater than 0,05, indicating that the means were statistically equal. Therefore, it can also be stated that the addition of 5 and 10% RBP does not affect the compressive strength of C25 concrete at 7, 28, and 56 days, a result similar to that of C20 concrete.

It is observed that every mixture shows an increasing resistance to compression over time due to cement hydration and pozzolanic reaction. The latter is caused by the active particles of SiO_2, Fe_2O_3, and Al_2O_3 (Table 1) present in RBP, which react with calcium hydroxide (CH) to form C-S-H, C-A-H, and C-A-S-H gel (Shao *et al*., 2019). In most cases, it is observed that the compressive strength of the reference is higher on average than that of the mixtures including RBP. This is due to the clinker dilution effect, which reduces the amount of hydrated products (Luo *et al*., 2022).

On the other hand, it can be observed that mixtures including 5% RBP at the seven-day stage exhibit a higher compressive strength (on average) than the reference. Shao *et al*. (2019) point out that RBP has a filler effect, which develops at the first stages of cement-based materials. In this case, it was up to 7 days and only for 5% RBP. Subsequently, the filler effect was reduced as the stages went by.

Figure 9 shows the microstructure of mixtures including RBP at 28 days, where hydrated products are observed, mainly C-S-H and ettringite (AFt). However, CH could not be distinguished, which would indicate its partial consumption by pozzolanic reaction (Ortega *et al*., 2018; Luo *et al*., 2022; Wong *et al*., 2018).

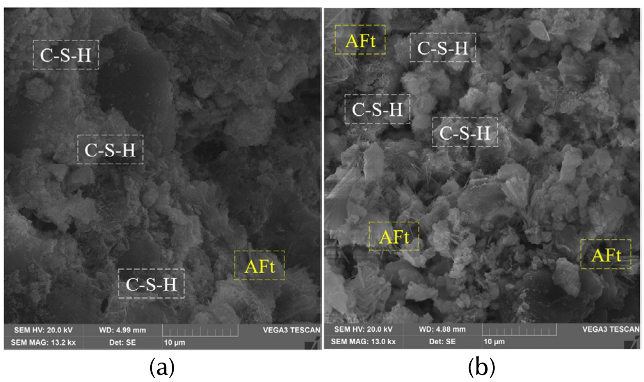


Figure 9. Microstructure of mixtures including a) 5% RBP and b) 10% RBP
Source: Authors

The literature reports that cement-based materials decrease in compressive strength as the RBP proportion increases (Shao *et al*., 2019; Duan *et al*., 2020; He *et al*., 2021). However, the hydration products obtained by pozzolanic reaction were beneficial, as the compressive strength of every mixture statistically remained similar to the reference (up to 10% RBP). This may be due to pore refinement by pozzolanic activity and the filler effect (Ortega *et al*., 2018). In this sense, several authors suggest using lower replacement percentages (~10-20% RBP) to avoid reduction – and even increase compressive strength (Schackow *et al*., 2015; Toledo Filho *et al*., 2007; Ma *et al*., 2020b).

The results are similar to those reported by Arif *et al*. (2021), who indicated a positive variation of 5,43% in the compressive strength of 5% RBP after 28 days. Liu *et al*. (2020) also reported that the compressive strength is comparable to the reference in replacements of up to 10% RBP, highlighting the influence of particle size in maintaining or improving the mechanical properties of mortars. Similarly, Wang *et al*. (2022) indicated that, for advanced ages, 10% RBP only reduces the compressive strength by 5%, which suggests that the pozzolanic reaction of RBP has an influence at later ages. Although literature may report variations in compressive strength with the use of RBP (for replacements of up to 10%), these differences are not significant, which was also verified in our study. However, higher substitution percentages and a larger particle size can significantly affect compressive strength. On the other hand, it is important to mention that the RBP used did not require additional treatment, for example, chemical activation, which highlights the benefits of its use in terms of energy expenditure and economic feasibility.

Tensile strength by diametrical compression

Figures 10 and 11 present the results obtained regarding tensile strength by diametrical compression for the C20 and C25 mixes. For C20, this aspect shows a tendency to decrease, except for 5% RBP after 28 days, where an increase of 1,71% is observed. Through the ANOVA, significant differences are noted between the means of the mixes after 7 (p-value=0,004), 28 (p-value=0,014), and 56 days (p-value=0,028). Table 5 shows that the reference means and those of 5% RBP are the same, thus indicating that no reduction in tensile strength takes place for this RBP percentage.

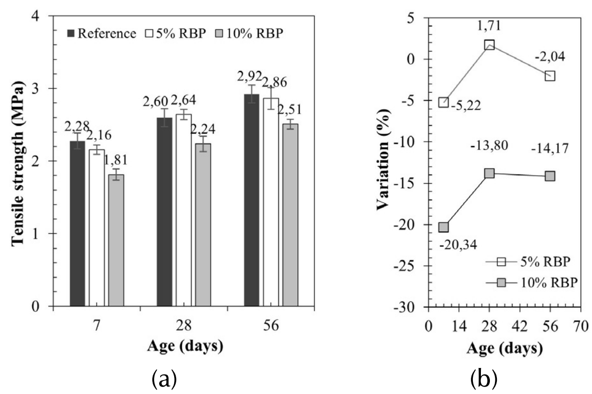


Figure 10. a) Tensile strength for C20. b) Tensile strength variation regarding the reference.
Source: Authors

Table 5. Tukey's test for the tensile strength of C20

Group 1	Group 2	p-value		
		7 days	28 days	56 days
Reference	5% RBP	0,408	0,902	0,877
Reference	10% RBP	0,004	0,029	0,032
5% RBP	10% RBP	0,017	0,018	0,059

Source: Authors

Every C25 mixture shows a trend similar to the results obtained with C20, as well as reductions in tensile strength. Through the ANOVA, significant differences for the ages of 7 (p-value=0,001), 14 (p-value=0,021), and 28 days (p-value=0,037) are found. It can be stated that the tensile strength means of the reference and those of 5% RBP are the same (Table 6). However, note that, after 28 and 56 days, there is no difference in average tensile strength for 5 and 10% RBP.

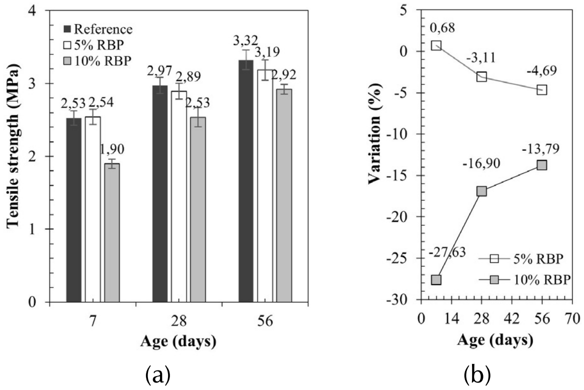


Figure 11. a) Tensile strength for C25. b) Tensile strength variation regarding the reference.
Source: Authors

Table 6. Tukey's test for the tensile strength of C25

Group 1	Group 2	p-value		
		7 days	28 days	56 days
Reference	5% RBP	0,984	0,779	0,516
Reference	10% RBP	0,001	0,022	0,033
5% RBP	10% RBP	0,001	0,051	0,141

Source: Authors

In general, it has been reported that using RBP in smaller amounts does not significantly influence tensile strength (Ge *et al.*, 2015; Ortega *et al.*, 2018). The results follow the same trend regarding compressive strength, where IP 40 cement dilution is observed. However, RBP's pozzolanic reaction leads to forming C-S-H gel (He *et al.*, 2021), which compensates for the dilution effect in the 5% replacement. A replacement of 10% RBP entails a significant reduction, indicating that the mechanical resistance of the cement matrix was negatively affected. Irki *et al.* (2018) pointed out that tensile strength increases as the RBP fineness and SSA increase, but the RBP used has a similar SSA to that of IP 40 cement as well as a higher D50, so this effect was not observed.

Water absorption, specific mass, and void index

Figures 12, 13 and 14 present the physical properties of C20 and C25. On the one hand, it is observed that a 5% RBP replacement reduces absorption, increases density, and reduces the void content of every mixture. On the other hand, a 10% RBP replacement reduces absorption, density, and voids to a lesser extent when compared to the former, regardless of design strength.

Although a decrease in water absorption is observed when including RBP, there is a predominance for 5% RBP, especially in C25, with a reduction of 10,24%. Through the ANOVA, it is confirmed that there are differences between means of C20 (p-value=0,028) and C25 (p-value=0,004). In the case of C20, only a difference between the reference and 5% RBP is noted (Table 7). For C25, differences between two pairs of mixes are evidenced (Table 8). These results follow the same trend as those of C20, indicating that a 5% RBP replacement has a positive influence on absorption (reduction) and that higher RBP percentages do not show variations in this regard.

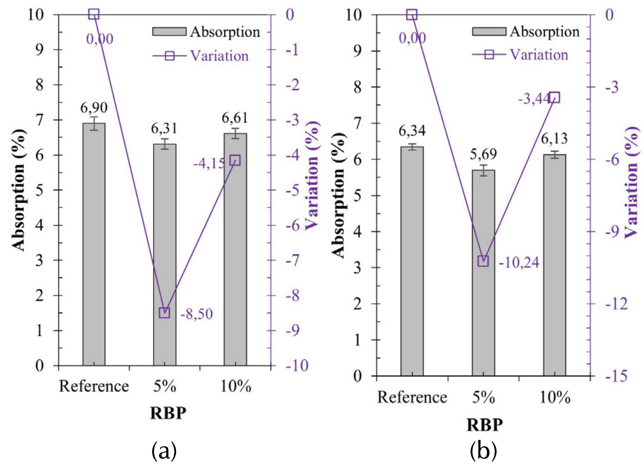


Figure 12. Water absorption for a) C20 and b) C25
Source: Authors

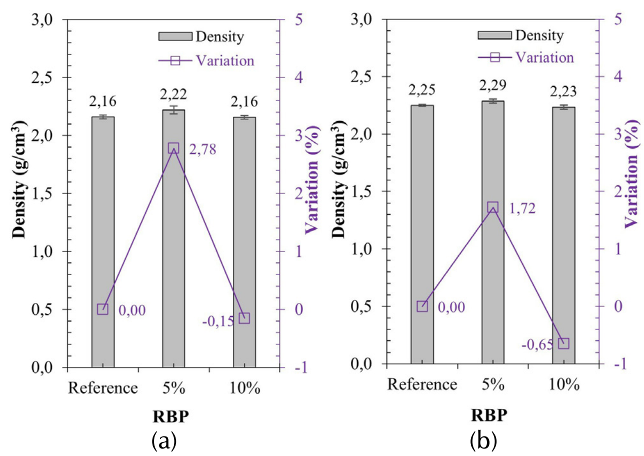


Figure 13. Density for a) C20 and b) C25
Source: Authors

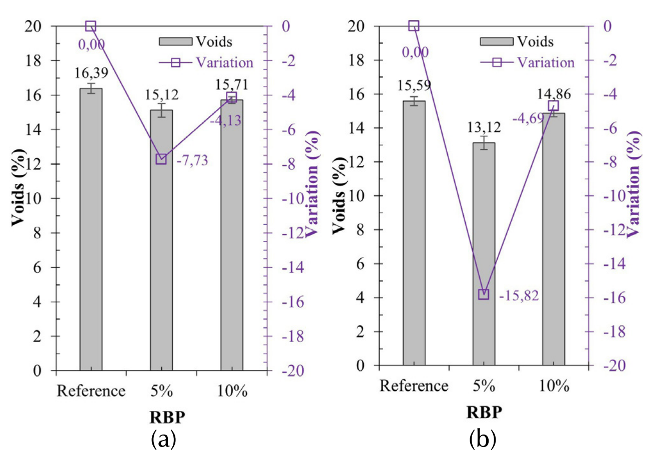


Figure 14. Voids for a) C20 and b) C25
Source: Authors

A 5% RBP replacement increases the density by 2,78 and 1,72% in C20 and C25, respectively, while 10% RBP minimally reduces it to 0,15 and 0,65%. Through the ANOVA, it is confirmed that there are differences between the means of the C25 mixes (p-value=0,037), as opposed to C20 (p-value=0,073). However, for C25, only 5 and 10% RBP mixtures show differences (Table 8). The results indicate that cement replaced by up to 10% RBP does not significantly impact density.

Table 7. Tukey's test for the physical features of C20

Group 1	Group 2	p-value		
		Absorption	Density	Voids
Reference	5% RBP	0,024	0,111	0,015
Reference	10% RBP	0,248	0,989	0,153
5% RBP	10% RBP	0,223	0,093	0,217

Source: Authors

Table 8. Tukey's test for the physical features of C25

Group 1	Group 2	p-value		
		Absorption	Density	Voids
Reference	5% RBP	0,004	0,111	0,001
Reference	10% RBP	0,235	0,651	0,103
5% RBP	10% RBP	0,025	0,035	0,002

Source: Authors

The void content also shows the same trend as the absorption results. A greater reduction in mixes including 5% RBP is noted, highlighting 15,82% for C25. A 10% RBP proportion yields lower reduction results when compared to those of 5% RBP. The ANOVA shows void content means with significant differences for C20 (p-value=0,018) and C25 (p-value=0,001). For both design resistances, there is a difference between the reference and 5% RBP, as well as a significant difference between 5 and 10% RBP only for C25.

Schackow *et al*. (2015) reported that the values of apparent porosity and water absorption in mixes including RBP remain within the same range as the reference. In our case, the mixes including 5% RBP show a less porous structure. This is also corroborated by the density results, where, on average, the mixes with 5% RBP exhibit an increase, indicating that RBP particles can fill and reduce the volume of the pores due to physical effects and the pozzolanic reaction of amorphous compounds present in RBP. Likes *et al*. (2022) also point out that RBP yields mixes with higher density, which is due to the granulometry of RBP creating a complete particle distribution when combined with Portland cement.

Note that 5% RBP improved the physical properties of the concretes, such as absorption and their void index, which were reduced. This is attributed to the filling effect and pozzolanic reactions, whereby the new hydration products are located in the capillary pores, refining them, resulting in an improved cementitious matrix (Ma *et al*., 2020a). On the contrary, the use of 10% RBP did not yield these positive effects; the physical properties were similar to those of the reference, indicating a compensation between the dilution effect of Portland cement and the filling effect and pozzolanic reactions. Liu *et al*. (2020) also pointed out that the porosity of mortars with RBP is equal to those of the reference; even a replacement of up to 30% RBP could show the same tendency, albeit with the use of finer RBP particles (0-0,045 mm). Regarding density, these authors also indicated that there is no significant difference with the use of RBP. Wang *et al*. (2022) noted that, despite the dilution effect of RBP (up to 20% RBP), secondary hydration (pozzolanic reaction) could refine the matrix pores. Ma *et al*. (2020a) reported the same results for a particle size D50 = 42 μm, where the water absorption of replacements of up to 15% RBP was similar to the reference. Therefore, physical properties depend on the percentages of fineness and substitution. In this case, the percentages (up to 10%) and the particle size (D50=27,99 μm) employed could maintain and/or improve the physical properties of the concretes.

Conclusions

Directly extracted from demolition and construction sites, and without the need for pre-treatments, RBP may be used as an SCM, replacing Portland cement to produce concrete. RBP stands out for its pozzolanic activity, it reduces cement consumption, and its mechanical resistance is similar to that of the reference, especially its resistance to compression. Tensile strength is compromised by a 10% RBP replacement, which was observed in both C20 and C25 strength designs.

Mixtures including RBP lose workability, which is due to the size, shape, and rough texture of RBP particles. However, 5% RBP did not entail changes in workability, being statistically similar to the reference. For 10% RBP, using superplasticizers could be considered in order to improve this property.

Replacing Portland cement with 5% RBP benefits the physical properties of concrete. Its absorption and void content are reduced, and the density of any mix is slightly improved, which indicates a refining of the porous structure. On the other hand, using 10% RBP maintains the physical characteristics of the reference.

Both 5 and 10% RBP are suitable for use in structural concrete, regardless of the design resistance (C20 or C25). Although 10% RBP reduces the tensile strength, this property is not considered when calculating reinforced concrete structures. Therefore, the proposed RBP-added concretes are viable for use in the construction industry, as their physical-mechanical properties were equal to the reference. However, in order to increase their mechanical resistance, the RBP particle size could be reduced and, therefore, its SSA could be increased, thus improving the physical effect.

Using RBP as a replacement for Portland cement represents a sustainable approach in the construction industry. On the one hand, reducing the amount of Portland cement results in less CO_2 emissions. On the other hand, any waste would be reused and would prevent disposal in landfills. Nevertheless, future works could determine the CO_2 reductions derived from the use of RBP as a partial substitute for Portland cement, which will make it possible to more accurately determine the sustainability of the proposal.

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Author contributions

JHAR conceived the idea and did the background research. BMMR collected the data, developed the workflow, and performed assessments. RDTF provided critical feedback. JHAR led the drafting process and wrote the main part of the manuscript, to which all authors contributed.

Conflicts of interest

The authors have no conflicts of interest to declare.

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