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RESEARCH ARTICLE

Microstructure and mechanical properties of ternary mortars with brick powder, glass powder, slag, fly ash, and limestone

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Abstract
The objective of this research is to study the effects produced by ternary binders which combine the addition of waste brick powder with fly ash, limestone, ground granulated blast furnace slag or waste glass powder in the microstructure and mechanical properties of mortars. In these ternary binders, the ordinary Portland cement was partially replaced by 10% of waste brick powder and 10% of another of the abovementioned additions. Mortars prepared with ordinary Portland cement without additions were also prepared. The microstructure was characterized with mercury intrusion porosimetry, electrical resistivity, and thermogravimetric analyses. Ultrasonic pulse velocity, compressive and flexural strengths were also determined. Mortars made using ternary binders with two active additions showed higher pore refinement and higher electrical resistivity at 250 days. Furthermore, their compressive strength and ultrasonic pulse velocity were relatively similar or even higher than that noted for reference specimens.

KEYWORDS
binders/binding, glass, mechanical properties, microstructure, waste brick powder

1 | INTRODUCTION

Nowadays, the reduction of the global warming is a major issue. In this line, the search of ways for lessening the greenhouse gases emissions constitutes a wide field of investigation.[1–3] For contributing to reach the global sustainable development goals, the construction sector has put into practice several strategies, such as the development of more eco-friendly materials,[4,5] with the incorporation of additions and the use of recycled or lightweight aggregates.

Regarding the cement industry in particular, the production of sustainable cements with additions is becoming increasingly popular.[6–8] The majority of these additions are residues originated in other industrial sectors, so their reuse is also interesting in order to reduce the environmental damages produced by their storage in specific installations. Furthermore, the use of additions may also provide a beneficial influence in the performance of cement-based materials.[9–11] Then, at present the research related to the effects of the additions and the assessment of new sustainable cementitious materials for developing eco-friendly cements, still constitutes an important topic of study.

On one hand, there are standardized additions, such as ground granulated blast furnace slag,[12] silica fume,[13] fly ash,[9] and limestone.[14] Among those additions, silica fume and fly ash have pozzolanic activity, which means that their components can react with portlandite produced along the clinker hydration, resulting in the formation of additional hydrated products, which entails an improvement of pore structure and properties of the material.[9,15–20] For ground granulated blast furnace slag, this addition develops hydraulic activity, so it is able to react directly with water, forming new calcium-silicate-hydrate (CSH) phases, also enhancing the pore network and overall performance of cement-based materials.[21–23] Limestone addition lacks hydraulic or pozzolanic activity,[14,24] although it can act as filler, influencing in this way the microstructure and properties. On other hand, several examples of new additions, recently developed, are rice husk ash,[25] brick powder,[19] volcanic powder,[26] red mud,[27] and glass powder,[28] among others. It has been reported that the abovementioned new additions have pozzolanic activity[19,25–28] and in the case of brick powder, it develops both pozzolanic and filler effects.[19,20,29–31]

Moreover, in relation to the sustainable cements with additions, most of the research performed is generally focused on the study of binary binders, in which clinker is partially replaced by one addition. However, the exploration of the performance of cement-based materials made with ternary binders,[14,32,33] in which clinker is substituted in part by two additions, may constitute an interesting field of investigation for providing more alternatives to develop eco-friendly cements. In these ternary binders, to incorporate two additions could bring a better behavior of the materials, due to the possible synergetic effects of their combination,[34–36] especially when standardized and new additions are blended in these binders.

Therefore, the main objective of this research is to study the effects produced by ternary binders which combine the additions of waste brick powder, fly ash, limestone, ground granulated blast furnace slag, and waste glass powder in the microstructure and mechanical properties of mortars. In these ternary binders, the ordinary Portland cement was partially replaced by 10% of waste brick powder and 10% of another of the abovementioned additions. Furthermore, reference mortars made using ordinary Portland cement without additions were also prepared. In order to get information about the microstructure of the mortars mercury intrusion porosimetry, electrical resistivity measurements, and thermogravimetric analyses were performed. Lastly, regarding the mechanical performance of the mortars, ultrasonic pulse velocity (UPV), compressive and flexural strengths were also obtained.

2 | EXPERIMENTAL PROCEDURES

2.1 | Materials and sample preparation

In this research, mortars made with different ternary binders were studied. All these binders incorporated waste brick powder as addition, which was combined with waste glass powder, ground granulated blast furnace slag, fly ash, and limestone, replacing commercial ordinary Portland cement CEM I 42.5 R (Spanish and European standard UNE-EN 197-1[37]).

Firstly, reference mortars were prepared using ordinary Portland cement without additions, CEM I 42.5 R,[37] which were named as REF in the presentation of results. Regarding the mortars with ternary binders, the cement CEM I 42.5 R was partially replaced by 10% (in weight) of waste brick powder and 10% of another of the abovementioned additions. Therefore, four ternary binders were studied, which were designated as FA-BP, L-BP, S-BP, and GP-BP, incorporating fly ash, limestone, ground granulated blast furnace slag, and waste glass powder, respectively, together with brick powder. For making easier the comprehension of the meaning of the different designations of the binders, they are compiled in Table 1.

In relation to the additions used in this work, the brick powder came from industrial brick residuals from demolition debris. These bricks are standardized bricks commonly used in building construction and in their manufacture process[38] they are fired at a maximum temperature of 1000°C, in which crystalline structures of clay silicates are transformed in amorphous compounds which pozzolanic activity. Here, the brick powder was sifted and only particles under 75 μm were used as addition. The complete characterization of the brick powder used here can be consulted in the work of Letelier et al.[39] The waste glass powder used as addition in the ternary binders was obtained with a process of crushing and dry grinding of the original glass residues, which came from recycled containers. The characteristics of waste glass powder addition used in this research were reported by Letelier et al.[40] and Tremiño et al.[41] On the other hand, the additions of fly ash, ground granulated blast furnace slag, and limestone accomplished the prescriptions of the UNE-EN 197-1 standard[37] for being used in the manufacture of commercial cements. These three standardized additions were

TABLE 1 Designation of the mortars studied and percentage (in weight) of CEM I and additions

Designation	CEM I 42.5 R (%)	Brick powder (%)	Fly ash (%)	Limestone (%)	Blast furnace slag (%)	Glass powder (%)
REF	100	–	–	–	–	–
FA-BP	80	10	10	–	–	–
L-BP	80	10	–	10	–	–
S-BP	80	10	–	–	10	–
GP-BP	80	10	–	–	–	10

TABLE 2 Chemical composition of brick powder, fly ash, limestone blast furnace slag, and glass powder (in weight %)

Components	Brick powder (%)	Fly ash (%)	Limestone (%)	Blast furnace slag (%)	Glass powder (%)
MgO	–	1.40	0.47	6.98	–
Al_2O_3	39.05	27.70	1.22	10.10	2.90
SiO_2	41.47	54.40	2.85	31.50	64.32
SO_3	1.59	0.53	0.10	1.94	–
K_2O	2.81	3.12	0.18	0.52	1.56
CaO	0.63	2.55	94.40	46.80	18.18
TiO_2	1.03	1.05	0.11	0.94	–
Fe_2O_3	12.73	8.06	0.54	0.37	–
P_2O_5	–	0.46	0.02	0.02	–
Na_2O	–	–	–	0.30	13.03
CuO	0.70	–	–	–	–

provided by the company Cementos Portland Valderrivas (Spain) and at present they are used in the commercial blended cements produced by this company. The chemical compositions of these five additions used are shown in Table 2. The mineralogical study of the brick powder, slag, fly ash, and limestone was carried out using X-ray diffraction (XRD) (see Figure S1).

The water to binder ratio was 0.5 and the aggregate to cement ratio was 3:1 for all the mortars series. The fine aggregate accomplished the prescriptions of standard UNE-EN 196-1.[42]

Three types of samples were made. The first one consisted of prismatic samples with dimensions 4 cm × 4 cm × 16 cm. The second kind was cylindrical specimens with dimensions 5 cm diameter and 6 cm height. Finally, another type of cylindrical samples was prepared, now with 10 cm diameter and 22 cm height.

All the samples were stored in a chamber with 95% relative humidity (RH) and 20°C temperature during the first 24 h since setting. Once finished that initial curing, the specimens were de-molded, being kept in an optimum laboratory condition (20°C and 100% RH) until the testing ages,[43] which were 28 and 250 hardening days.

2.2 | Microstructure characterization

The evolution of the microstructure of the analyzed mortars has been analyzed with mercury intrusion porosimetry,[44,45] thermogravimetric analyses, and measuring the electrical resistivity.[46,47]

The mercury intrusion porosimetry test was performed using a Poremaster-60 GT porosimeter manufactured by Quantachrome Instruments (Boynton Beach, FL, USA). The results analyzed were total porosity and pore size distribution. The conditioning of the samples before the test was done according to the procedure explained by Ibáñez-Gosálvez et al.,[43] as well as the distribution of pores by size ranges. Two measurements were made on each type of mortar at both hardening ages studied. The samples tested were pieces obtained from cylinders with 5 cm diameter and 6 cm height.

The electrical resistivity was determined using the nondestructive Wenner four-point test, according to the Spanish standard UNE 83988-2,[48] using a Proceq analyzer on cylindrical samples with 22 cm height with 10 cm diameter at different ages until 250 days. Three different samples were tested for each mortar type and four measurements were made per sample at each testing age.

The thermogravimetric analyses were performed according to Ibáñez-Gosálvez et al.[43] A simultaneous thermogravimetry-differential thermal analyzer (TG-DTA) model TGA/SDTA851e/SF/1100 manufactured by Mettler Toledo was used. The area of portlandite peak has been studied at 28 and 250 days. Three measurements were made on each binder. The powder samples tested with this technique were obtained from milling pieces obtained from cylindrical specimens with dimensions 5 cm diameter and 6 cm height. Finally, in order to complement the discussion of the results of the microstructure characterization performed with the abovementioned techniques, scanning electron microscopy (SEM) images have been taken of the mortars, using a microscope model S3000N manufactured by Hitachi.

2.3 | Mechanical properties characterization

For characterizing the mechanical properties of the mortars studied, the compressive and flexural strengths and the UPV were studied. The strengths were obtained according to the Spanish and European standard UNE-EN 1015-11.[49] The UPV was determined according to the standard UNE-EN 12504-4,[50] using a Pundit Lab model of Proceq manufacturer (Schwerzenbach, Switzerland), following the same procedure than described by Ibáñez-Gosálvez et al.[43] For mechanical properties characterization, three prismatic samples with dimensions 4 cm × 4 cm × 16 cm were tested for each one of the studied binders along the studied time period.

3 | RESULTS

3.1 | Mercury intrusion porosimetry

The total porosity results obtained for the studied mortars are represented in Figure 1. At 28 days, the lowest values of this parameter were noted for REF specimens. In relation to the ternary binders, at that age mortars with fly ash (FA-BP series) and limestone (L-BP series) showed higher total porosities compared to those with slag (S-BP series) and glass powder (GP-BP series). Between 28 and 250 days, this parameter decreased for ternary binders, although this reduction was more noticeable for FA-BP and S-BP series. At 250 days, the lowest values of this parameter were observed for REF and S-BP mortars, nearly followed by GP-BP series, while it was higher for FA-BP and L-BP binders.

In relation to the pore size distributions obtained for the analyzed mortars, they are depicted in Figure 2. At both ages studied, the ternary binders showed a higher percentage of finer pores (size intervals <10 and 10–100 nm) in comparison with reference specimens. In addition, it has been noted an overall rise with age of the proportion of those finer pores for the majority of the binders. At 28 days, mortars with limestone (L-BP series) had a higher presence of pores with sizes lower than 100 nm than the rest of ternary binders. At 250 days, slight differences in this regard were observed, although the percentage of pores in the range <10 nm was lower for L-BP series, compared to other ternary binders.

3.2 | Electrical resistivity

The evolution with time of electrical resistivity is represented in Figure 3. In general, a rise with time of this parameter has been observed for all the mortars. At the initial age, reference samples showed a higher resistivity value than ternary binders. Since then, an important growth of this parameter was noted for these ternary mortars, while it hardly increased with time for reference specimens. The increasing rate was relatively similar for mortars with additions until 15 days approximately, when the electrical resistivity increase slowed down for the binder with limestone (L-BP series). This also happened for the binder with slag (S-BP series), although at a later age (around 28 days). From then to 250 days, the highest values of resistivity were observed for binders with fly ash (FA-BP series) and glass powder (GP-BP series), with scarce differences between them, followed by mortars with slag (S-BP series) and limestone (L-BP series). Lastly, the smallest electrical resistivity values corresponded to REF mortars over most of the time period studied.

3.3 | Thermogravimetric analysis

With respect to the thermogravimetric analyses performed, the derivate of weight versus temperature curves and the areas of the portlandite peak obtained for the studied mortars at 28 and 250 days can be observed in Figures 4 and 5, respectively. For reference mortars, it has been noted an increase of this parameter between both ages. In the case of ternary binders, it has been observed a reduction with time of their areas of the portlandite peak, which was more noticeable for S-BP, FA-BP, and GP-BP series.

3.4 | Mechanical strengths

The results of compressive strength are depicted in Figure 6. At 28 days, this parameter was lower for the ternary binder with glass powder (GP-BP series) com-

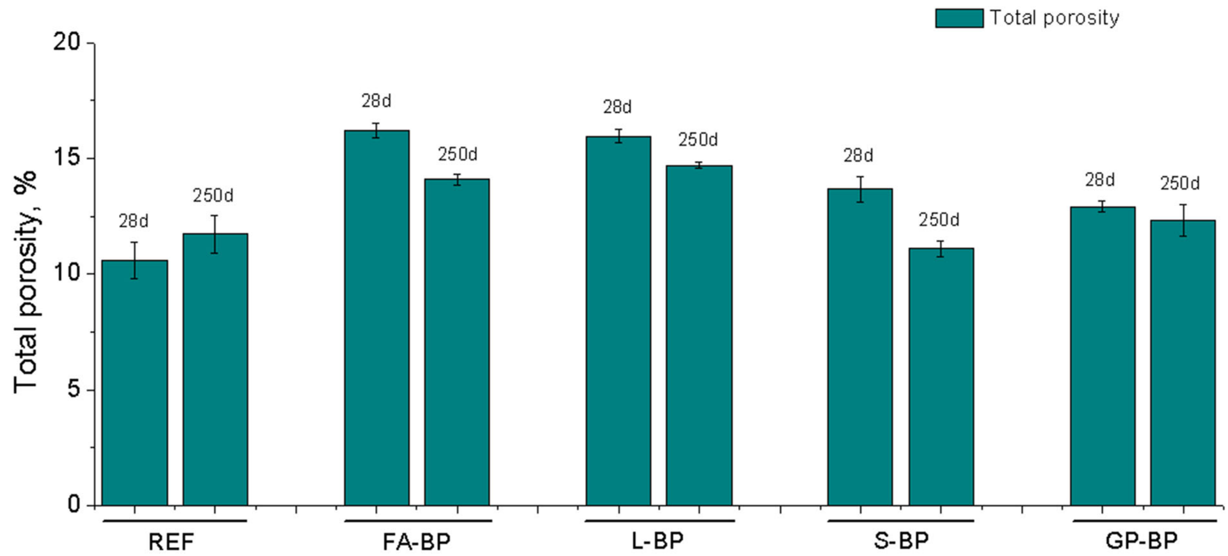

FIGURE 1 Total porosity obtained for the studied mortars

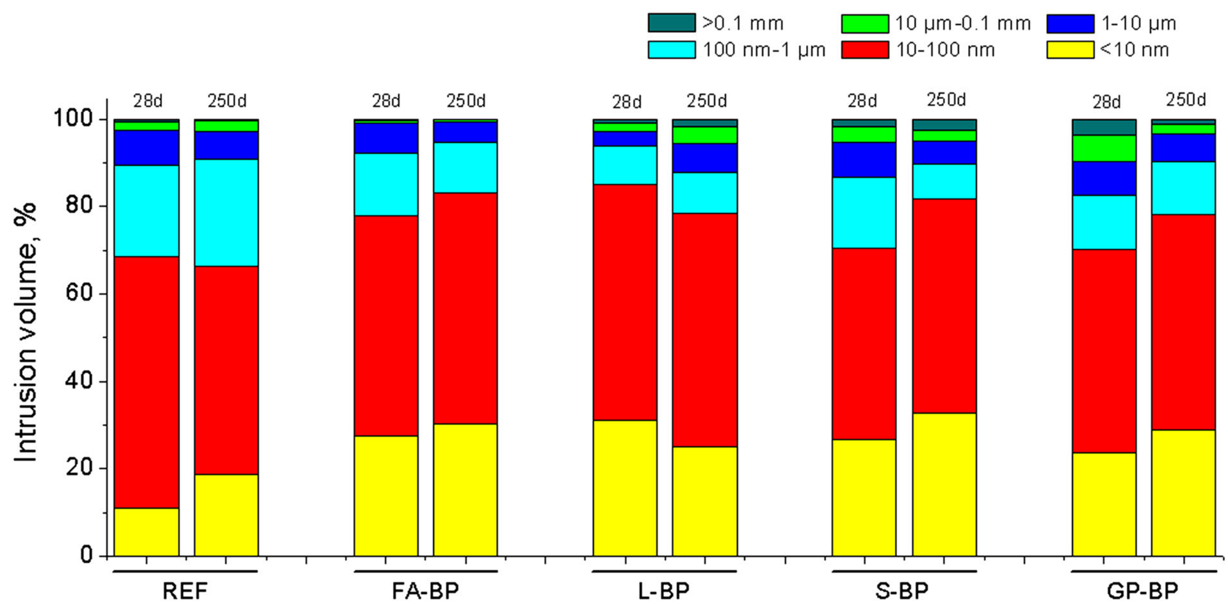

FIGURE 2 Pore size distributions noted for the analyzed binders at 28 and 250 days

pared to the rest of studied mortars, which showed a relatively similar compressive strength for all of them. Between 28 and 250 days, this parameter rose for all the analyzed mortars, except for L-BP series, whose compressive strength kept practically constant. At 250 days, the values of this parameter were similar for REF, FA-BP, and S-BP series, being slightly smaller for GP-BP binder compared to them. Finally, the lowest compressive strength at the last age studied was observed for L-BP mortars.

Regarding the flexural strength, its results can be observed in Figure 7. In general, not great differences in this parameter were observed, being this parameter in the range from 7 to 9 MPa for all the analyzed mortars. At 28 days, the highest flexural strength was noted for reference specimens, followed by those with limestone (L-BP series), and the rest of ternary binders showed relatively similar values of this strength. Between 28 and 250 days, this parameter hardly changed for REF, FA-BP, and L-BP series, while it noticeable increased for S-BP and GP-BP binders. At 250 days, the highest flexural strengths were obtained for REF and GP-BP mortars, nearly followed for ternary binder with slag (S-BP series). The lowest values of this strength at that last age were noted for FA-BP and L-BP

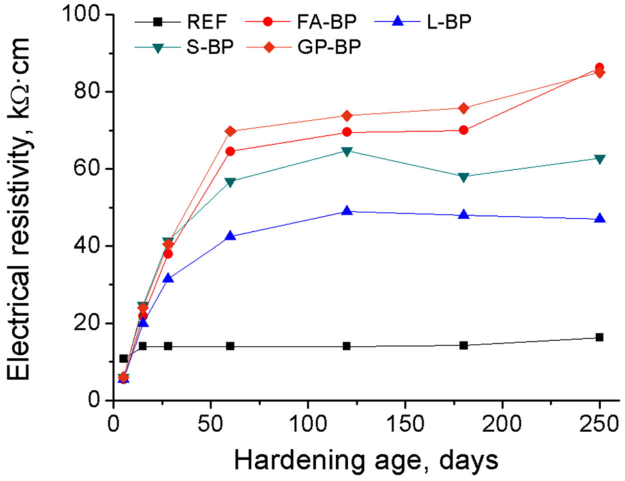

FIGURE 3 Evolution of the electrical resistivity for the different types of mortars tested

binders. Finally, similar trends with time of both compressive and flexural strengths have been observed in general for most of the mortars studied.

3.5 | Ultrasonic pulse velocity

The results of UPV are represented in Figure 8. This parameter showed an increasing trend for all the studied mortars. For ages under 50 days, the rising rate of UPV was higher than for later hardening times, when the increase of this parameter was slowed down. The overall differences in this parameter were not high between the analyzed binders. In the short term, the UPV was slightly greater for REF and FA-BP mortars, in comparison with the rest of binders. At later ages, the highest values of this parameter were noted for FA-BP series and the lowest for L-BP one, showing the rest of the binders very similar UPV, whose values were between those observed for the abovementioned series.

4 | DISCUSSION

In relation to the microstructure characterization, the higher percentage of finer pores noted in the pore size distributions of ternary binders compared to reference mortars (see Figure 2) would indicate that these binders had a higher pore refinement. This result would be related to the effects of the additions incorporated to the binders. First of all, several authors[19,30] have reported that brick powder has pozzolanic activity, which would allow that the components of this addition can react with the portlandite formed as product of clinker hydration, giving as a result new solids phases which would progressively reduce the pore sizes. Furthermore, this addition would also have a filler effect,[31] contributing in this way to close the microstructure. This influence of brick powder would be produced in all ternary binders, because this addition was present in all of them. Regarding fly ash and glass powder, both additions also have pozzolanic activity,[9,18,51,52] which gives as a result the formation of new hydrated phases, producing a denser the microstructure of the material,[9,18,51,52] in a similar way that has been already explained for waste brick powder. On the other hand, the slag has hydraulic

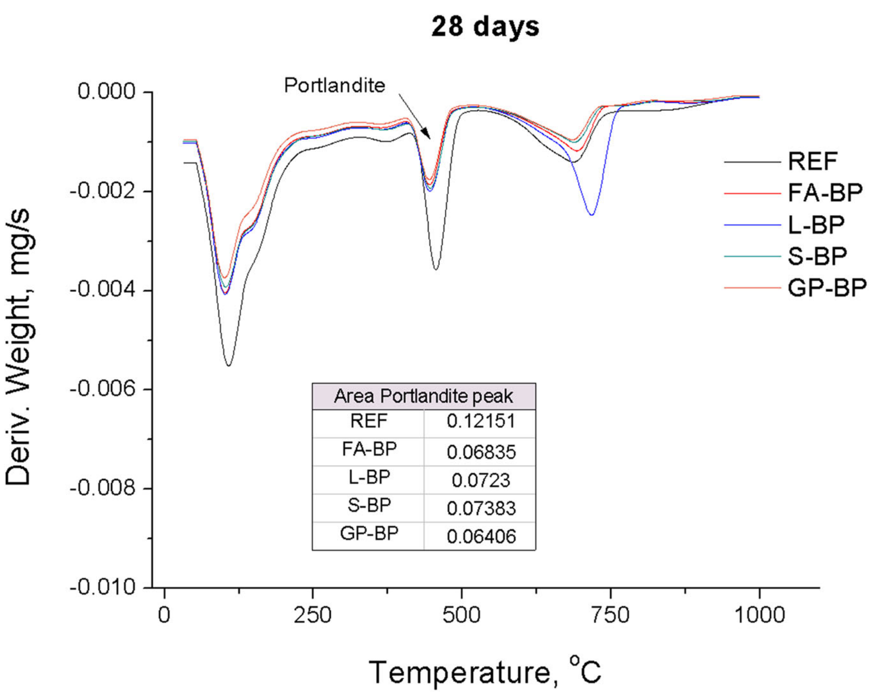

FIGURE 4 Derivate of weight versus temperature curves and areas of the portlandite peak obtained at 28 hardening days for the binders studied

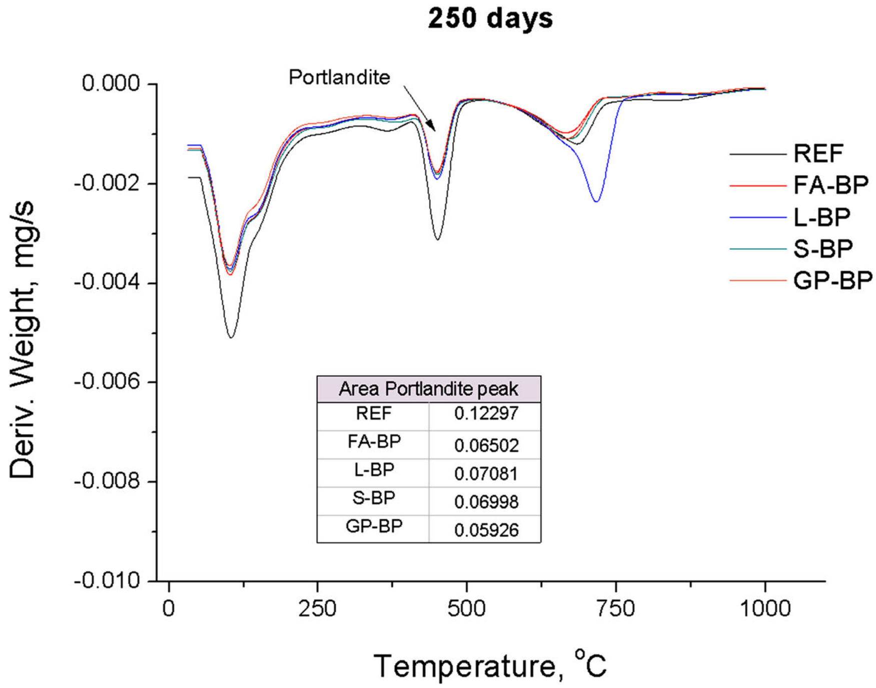

FIGURE 5 Derivate of weight versus temperature curves and areas of the portlandite peak obtained at 250 hardening days for the different mortars analyzed

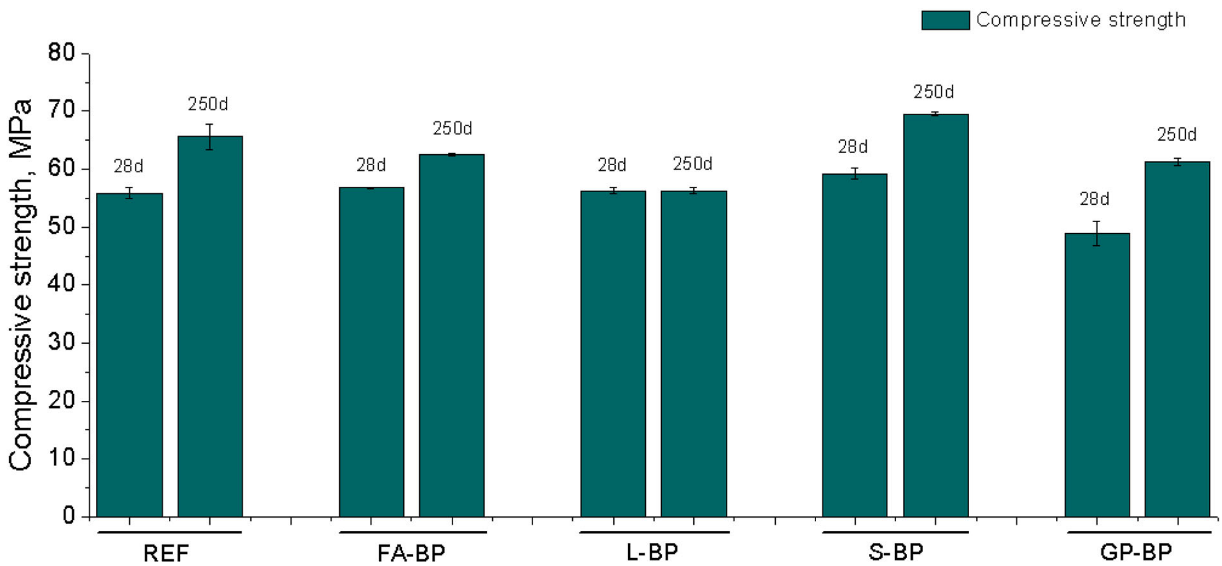

FIGURE 6 Evolution of the compressive strength observed at 28 and 250 days for the different series of mortars analyzed

activity,[53,54] so it can directly react with water, forming additional CSH phases, which would lessen the pore sizes[21] in the microstructure of the material. Finally, limestone addition lacks of hydraulic or pozzolanic activity, so it mainly has a filler effect in the pore network.[14,24,55]

Therefore, as has been explained, the five additions used for preparing the ternary binders would contribute to reach a more refined microstructure, being their effects in keeping with the pore size distributions results obtained. Moreover, the increase of finer pores overall noted for the studied mortars between 28 and 250 days, would be due to the progressive development of the abovementioned hydration and pozzolanic reactions, producing a higher pore refinement with time. This has been also observed for reference mortars without additions, being related in this case with the development of clinker hydration.[53,56]

Comparing the pore size distributions of the studied ternary binders, the higher pore refinement observed for the binder with brick powder and limestone (L-BP series) at 28 days, in comparison with the rest of binders, could be due to a possible synergy between the filler effect of both limestone[14,57] and brick powder,[31] combined with the

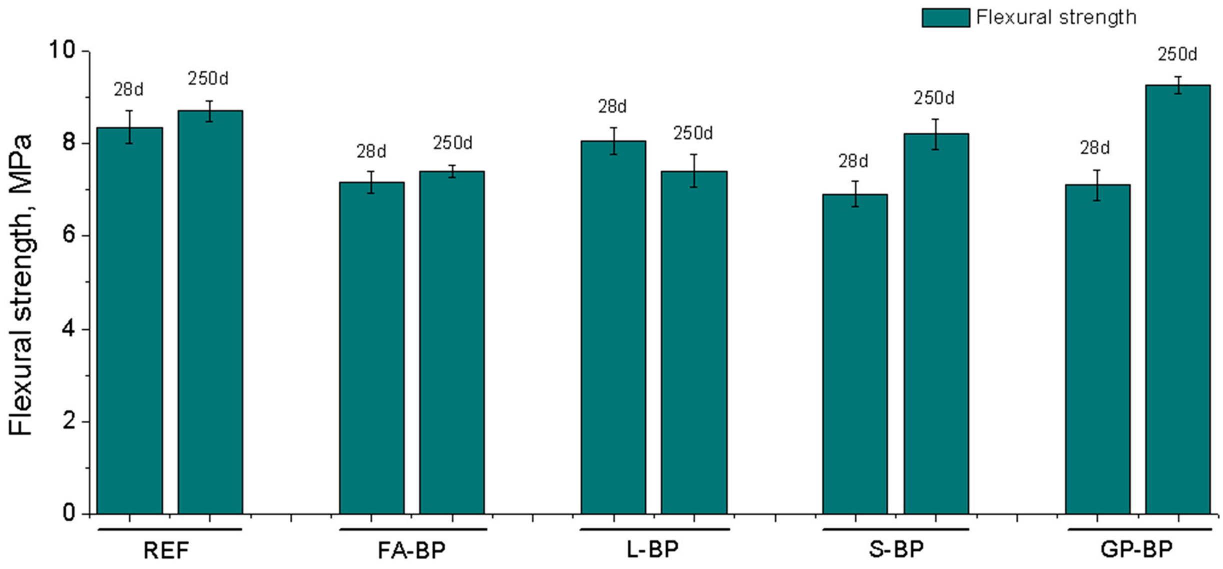

FIGURE 7 Results of flexural strength results obtained at 28 and 250 days for the studied mortars

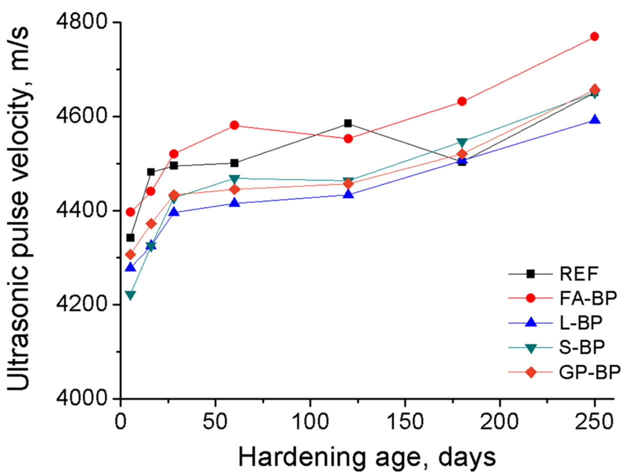

FIGURE 8 Evolution of ultrasonic pulse velocity for the analyzed binders

pozzolanic activity of this last addition.[19,30] Furthermore, the nucleation site effect of limestone addition, reported by other authors,[58] could be also help to increase the initial development of brick powder pozzolanic reactions, thus reducing the pore size in the short term. However, the lack of activity of limestone[57] would entail the scarce improvement of the microstructure at later ages noted for the mortar with this addition. In the case of the other active additions combined with brick powder (slag, glass powder, and fly ash), their effect as filler would be negligible, so their influence would not be as immediate as happened with limestone. In addition, more time would be needed to observe the influence of the development of their hydration and pozzolanic reactions,[9,18,22,52,59] which would agree with the slight delay of pore refinement at 28 days for FA-BP, S-BP, and GP-BP series compared to L-BP one. Despite that, the effects of those reactions were more noticeable in the long term,[9,18,22,52,59] as suggested the higher proportion of finer pores noted for those mortars with fly ash, slag, and glass powder at 250 days, to which could have also influenced the possible synergistic effects of combining them with brick powder in these binders.[20] In Figure S2, it has been included several SEM images of the mortars studied taken at 250 days. As can been observed, the pore refinement was relatively similar for binders with two active additions (FA-BP, S-BP, and GP-BP series), with a very compact microstructure in all of them. In order hand, at that age, the binder with limestone (L-BP series) showed lower refinement, and it can be still seen pores relatively high, without being completely filled (see Figure S2C), which would be compatible with the pore size distributions results.

Regarding the total porosity results (see Figure 1), the reduction with time of this parameter would be related to the development of hydration and pozzolanic reactions,[9,15,17,19,30,60] already explained. The solid phases formed as products of these reactions, would progressively close the pores, giving as a result lower porosity values, as has been observed. The result that additions with pozzolanic activity, such as fly ash and glass powder, did not produce a noticeable reduction of total porosity of cement-based materials, compared to reference mortars without additions, whereas they produced a significant pore refinement, would agree with the results pointed out by other authors.[22,41] However, the binder with slag and brick powder (S-BP series) reached similar total porosity values at 250 days than reference specimens, which could be explained in relation to the hydraulic activity of slag, which would have a more notable effect in the reduction of porosity, according to other works.[22,53]

The electrical resistivity is a useful parameter for obtaining information related to the connectivity of pores, as well as the evolution of the microstructure.[61] The rising trend with time of the resistivity generally observed (see Figure 3) would indicate a process of pore refinement with time,[62] with a reduction of larger pores, probably due to the formation of new solids as products of the hydration and pozzolanic reactions of the active additions incorporated to the studied binders.[9,17,19] This result would be in agreement with the progressive pore refinement noted in the pore size distributions previously discussed.

The higher initial resistivity values observed for reference specimens compared to ternary binders, would be related to a higher development of clinker in the very short term, while the effects slag hydration and particularly pozzolanic reactions of fly ash, brick powder, and glass powder were slightly delayed,[9,18,22,52,59] as suggested their lower first resistivity value measured. The effects of the abovementioned reactions would be later much more noticeable, as showed the higher electrical resistivity noted for ternary binders in comparison to reference series, agreeing with the greater presence of finer pores in their pore structure, revealed by mercury intrusion porosimetry. This result would be also in keeping with other authors,[62] which reported higher values of this parameter when supplementary cementitious materials are used.

The different evolution of electrical resistivity in the long term for the studied ternary binders would be related to the different additions combined in each one of them. The result that this parameter was firstly slowed down in the binder with limestone (L-BP series) would be related to the inert character of this addition,[14,24,55] without hydraulic or pozzolanic activity, so the synergetic effects of combining it with brick powder would be more limited in the long term. In the case of combining an active addition, such as slag, fly ash, and glass powder, with brick powder, their beneficial effects in the pore structure were more notable at later ages, as suggested the higher resistivity values noted for S-BP, FA-BP, and GP-BP series, which would be in consonance with their higher pore refinement at 250 days, compared to the rest of mortars studied. This could be explained due to greater formation of new solids phases as products of slag hydration and pozzolanic reactions of brick powder, glass powder, and fly ash, caused by the higher total content of active additions in the binder (20% in weight), in comparison with L-BP series, whose only active addition was brick powder, with a 10% content in weight of the binder. Furthermore, it seemed that these synergetic effects of incorporating two active additions in the binder were even more noticeable and extended over time when both additions had pozzolanic activity, as happened with FA-BP and GP-BP series, which showed their highest electrical resistivity values at later testing ages. This more prolonged influence in the long term of pozzolanic additions would be in keeping with other works.[9,17,22]

In relation to the results of the thermogravimetric analyses (see Figures 4 and 5), the increase of the area of portlandite peak noted for reference mortars between 28 and 250 days would suggest a rise of portlandite content due to the development of clinker hydration. On the other hand, this parameter decreased with time for ternary binders, which would be indicative of the portlandite consumption along the development of pozzolanic reactions of the active additions used in these binders. The more noticeable reduction of the area of portlandite peak in mortars with two active additions (S-BP, FA-BP, and GP-BP series) than in binder which combined limestone and brick powder (L-BP series) would be due to the presence of limestone, an addition without pozzolanic activity, as has been explained. These results would agree with those previously discussed for pore size distributions and electrical resistivity.

Regarding the mechanical properties, the results of compressive and flexural strengths (see Figures 6 and 7) showed coincidences with those obtained in the microstructure characterization previously discussed. The rise with time of both flexural and compressive strengths generally observed for all the mortars would be due to development of clinker and slag hydration, and pozzolanic reactions of fly ash, brick powder, and glass powder, which would produce an additional formation of solid phases, entailing an improvement of the mechanical performance of the material. This result would be in line with the pore refinement with time also noted. The effects in the long term of the lack of activity of limestone addition would be also noticeable in the compressive strength, which hardly grew with age for L-BP series. Moreover, it is interesting to highlight that at 250 days the compressive strength of ternary binders with two active additions (S-BP, FA-BP, and GP-BP series) hardly differed than that observed for reference specimens. This result was similar for flexural strength, although this parameter was slight lower for FA-BP series compared to S-BP and GP-BP binders.

The UPV allows getting additional information about the mechanical behavior of cement-based materials and the possible presence of defects and voids.[50,63] The increase with time of this parameter (see Figure 8) would agree with the overall rise of mechanical strengths from 28 to 250 hardening and with the gradual pore refinement. The higher UPV increasing rate in the short term would be a consequence of the initial development of hydration and pozzolanic reactions, which would progressively improve the mechanical behavior of the material. The relative small UPV differences at later ages among the analyzed mortars would be in keeping with the similar compressive strength noted at 250 days. Finally, the slight lower UPV values of L-BP series at the last age studied would coincide with its smaller compressive strength, related to the influence of limestone addition, as has been discussed.

Finally, it could be interesting to compare the results obtained for the binders studied in this work with those obtained for other mortars prepared with binders compatible with standardized cements type II,[43] incorporating only standardized additions, and with similar percentage of clinker replacement to that taken in this research. Regarding the microstructure characterization, the total porosity after 250 days of the L-BP binder improved the value noted for a CEM II mortar with only limestone as addition,[43] probably due to the abovementioned effect of pozzolanic activity of brick powder. Furthermore, this L-BP binder also showed in the long term similar total porosity to a CEM II ternary mortar with both fly ash and limestone additions,[43] which could be a relevant result, especially regarding the progressive reduction of fly ash production expected in Europe in the next years. Regarding the slag addition, at 28 days the S-BP binder showed higher porosity than a CEM II mortar with only this addition,[43] which may be related to the lack of hydraulic activity of the brick powder. Nevertheless, after 250 days, the total porosity was very similar for those mortars with slag, being mainly linked to the long-term influence of brick powder pozzolanic activity. Moreover, the S-BP binders presented lower total porosity at 250 days than the CEM II ternary mortars with slag studied by Ibáñez-Gosálvez et al.[43] In relation to the FA-BP binder, at 28 days it showed higher porosity values than all the CEM II binders analyzed in the previous work,[43] although in the long term this parameter was similar for FA-BP binder and the ternary CEM II mortar with fly ash and limestone. Lastly, for the GP-BP binder, it showed lower total porosity at 250 days than the binary CEM II mortars with limestone and fly ash and all the ternary binders studied by Ibáñez-Gosálvez et al.[43]

In relation to the pore size distributions, it is worth to highlight that all the ternary binders with brick powder analyzed in this research had higher pore refinement that those studied by the previous work of the authors.[43] This could be explained in terms of the filler effect of brick powder, which improved the pore network of the material since early ages, especially compared to standard CEM II mortars. In the long term, the ternary binders with brick powder still presented higher pore refinement, and the only CEM II mortars which showed similar refinement in the study of Ibáñez-Gosálvez et al.[43] were those with the binary binder with fly ash and the ternary binder with fly ash and limestone. The short-term effects of brick powder in the microstructure were also noticeable comparing the results of electrical resistivity obtained in this work and those noted in the previous research of the authors.[43] In particular, the ternary binders with brick powder showed a higher increase of the resistivity up to 50 days than the CEM II standardized mortars.[43] This result could be relevant because in some real applications (i.e., under aggressive conditions), it is requested a fast gain of durability properties, directly linked with electrical resistivity, for which the incorporation of brick powder in the ternary binder seemed to provide an advantage at relatively short ages, and in particular when this addition is combined with glass powder (GP-BP binder).

Regarding the mechanical properties, all the ternary binders with brick powder analyzed here showed higher compressive strength that the CEM II binary mortar with limestone studied by Ibáñez-Gosálvez et al.[43] In this line, it can be highlighted that S-BP binder had higher compressive strength at 28 and 250 days than all the CEM II binary and ternary mortars with slag tested in the previous work of the authors.[43] For FA-BP binder, it improved the strength of the CEM II ternary mortar with fly ash and limestone,[43] although in the long term it did not reached the values of this parameter noted for the other CEM II binders with fly ash.[43] In the case of GP-BP binder, its compressive strength at 250 days was higher than that observed by Ibáñez-Gosálvez et al.[43] for CEM II ternary mortars which combined limestone with slag and fly ash, respectively, which has also been observed for the L-BP binder. Lastly, the ternary binders with brick powder did not worsen the flexural strength in the long term of the mortars, in comparison with the standardized CEM II mortars analyzed in the previous research of the authors,[43] having all of them a similar order of magnitude in the range from 7 to 9 MPa.

5 | CONCLUSIONS

The main conclusions that can be drawn from the results previously discussed can be summarized as follows:

1. The analyzed mortars overall showed a progressive pore refinement with time, as suggested the increase of the proportion of finer pores, according to mercury intrusion porosimetry results, as well as to the rising trend of electrical resistivity. This pore refinement would be mainly due to the development of slag and clinker hydration and pozzolanic reactions of brick powder, fly ash, and glass powder, as suggested the thermogravimetric analyses performed.
2. The microstructure was more refined for mortars prepared with ternary binders in comparison with reference specimens without additions, as revealed the pore

size distributions and the electrical resistivity results. This could be due to the effects of hydration and pozzolanic reactions of the abovementioned additions, as well with the filler effect produced by limestone and brick powder.

3. The mechanical strengths and UPV of the mortars generally increased with time, being these results compatible with the progressive pore refinement revealed by microstructure characterization.
4. The comparison between the mortars prepared with ternary binders would reveal that those which combined two active additions (S-BP, FA-BP, and GP-BP series) showed higher pore refinement and higher electrical resistivity in the long term. Furthermore, their compressive strength and UPV were relatively similar or even higher than that noted for reference specimens. This could be explained in terms of their hydraulic or pozzolanic activity, producing synergies with the pozzolanic activity and filler effect of brick powder.
5. The ternary binder which combined limestone and brick powder (L-BP series) showed at later ages less pore refinement, lower electrical resistivity, lower compressive strength, and lower UPV values in comparison with the ternary binders which incorporated to active additions (S-BP, FA-BP, and GP-BP series). This would be due to the lack of hydraulic or pozzolanic activity of limestone addition.

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