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MECHANICAL AND DURABILITY PERFORMANCE OF CEMENTITIOUS MATRICES WITH LOW CEMENT AND DIFFERENT ADDITIONS

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Abstract.

Nowadays, the decarbonization of the concrete sector is a priority to counteract the global environmental harmful. Knowing that Portland cement is responsible for significant anthropogenic emissions worldwide, the optimization of cement dosage on concrete mixtures is a key issue, combined with the mechanical and durability performances, allowing to improve its eco-efficiency. The goal of the present work consists in optimizing the formulation of concrete matrices, used to produce reinforced concrete poles for the electric lines, by increasing the packing density, reducing the cement dosage and incorporating different additions, in order to promote the performance. Two different formulations of matrices were considered, fresh moulded concrete with dry consistency and formwork moulded concrete with plastic consistency. For each one, different dosages of cement and various additions (limestone filler, fly ash, natural pozzolan, electric furnace slag) were considered to replace the cement, which were used single or combined. The mortar matrices of the concrete formulation were characterised regarding: fresh properties; mechanical properties (flexural and compressive strengths and Young's modulus); shrinkage and durability properties (capillary water absorption, carbonation and chloride ingression resistances). The influence of the additions on those properties was analysed and compared with reference cement-based mixtures and the main conclusions are presented.

Keywords: Additions, durability, formulation optimization, low cement concrete, mechanical performance.

1. Introduction

Eco-efficient and economical concrete production has been achieved, among other strategies, by partially replacing Portland cement with by-products from other industries. The great potential for the impact reduction of the environmental footprint related to cement production has been seen especially for concretes with current strengths, but also for high and ultra-high strengths. The granulometric optimization, combined with the use of cement with high reactivity and additions as cement substitutes, and the use of powerful superplasticizers together with the reduction of water dosage, allow a significant reduction of the clinker present in Portland cement, which enables the production of concretes with low cement dosages and good mechanical performance [1, 2]. This evolution, from conventional mixtures to eco-efficient concrete, which is expected to be proved by studies of life cycle analysis, should not diminish the performance of cementitious materials and must take into account their workability, strength and durability performances. Optimizing the formulation of this concrete has a potential positive influence on mechanical properties at longer ages due to pozzolanic effect, as well as also on time dependent and on durability properties. Although the development of the initial strengths is slower compared to traditional concretes, it is possible to obtain concrete with higher mechanical strengths at older ages, because the pozzolanic reactions are slow but prolonged [2–4].

Optimizing packing density is not only beneficial for reducing the water amount, but can also reduce the space between cement particles. To optimize the packing density of the concrete, these should be selected to fill the voids between large particles with smaller particles and so on to obtain a dense and stiff structure of concrete matrix, reducing the space that needs to be filled by hydration products, which results in higher strengths. The volume of water required to ensure workability can also be reduced by adding superplasticizers in the matrix [3–5].

The published works on this subject indicates that, in the production of eco-efficient concrete, a signifi-

Mixture	Binder	Cement	Fly Ash	Lim. filler	Pozz	Slag	Sand mix.	Coarse Aggr. mix.	W/B	Compact-ness
	(kg/m^3)	(kg/m^3)	(kg/m^3)	(kg/m^3)	(kg/m^3)	(kg/m^3)	(kg/m^3)	(kg/m^3)	(−)	(−)
BT ref	400	400	–	–	–	–	930	902	0.390	0.824
BT200 FA	350	200	150	–	–	–	804	1144	0.312	0.865
BT250	350	250	50	50	–	–	829	1129	0.323	0.860
BT200 Poz	350	200	–	–	150	–	797	1138	0.326	0.860
BT250 Slag	350	250	–	50	–	50	861	1120	0.323	0.860
MT ref	360	360	–	–	–	–	778	1046	0.472	0.808
MT250 FA	350	250	100	–	–	–	902	992	0.409	0.840
MT+200 FA	400	200	200	–	–	–	888	920	0.370	0.835
MT250 Poz	350	250	–	–	100	–	902	992	0.408	0.840
MT250 Slag	350	250	–	–	–	100	957	982	0.408	0.840

Table 1. Formulation of concrete mixtures used to produce the mortar matrices.

cant reduction in the amount of cement is achieved without changing the properties of the mixtures, thus reducing CO2 emissions per cubic meter of concrete in 25% [3, 6]. Filer and fly ash, for example, have been identified as viable additions with visible improvements in workability, mechanical properties and durability [1, 2]. Fly ash is a by-product with moderate cost and an efficient addition to replace cement in concrete mixtures, with good results to assure strength and durability. However, its growing demand and uncertain availability in developed countries, also due to environmental concerns, demands alternative additions, such as natural pozzolans or other by-products, like slags. Some studies point to more than 65% reduction in environmental impact when blast furnace slag is used for partial cement replacement [2]. Industrial concrete, both in precast and ready-mixed production, is not optimized in terms of formulation or cost and efficiency. Dosages of Portland cement should be minimized to reduce production costs and to be more concerned with eco-efficiency, by including more additions in formulation. Also, by maximizing the packing density and densification of the binder matrix, it makes the matrix more closed and provides greater durability and high mechanical strength with lower cement content. In this sense, mixtures in mortar matrix of the concrete, considering the partial replacement of cement by different additions such as limestone filer, fly ash, natural pozzolans or ground electric furnace slag, were studied in the present work, promoting sustainable concrete solutions. Two types of mixtures were studied: one with dry consistency for fresh moulded concrete - BT and another with plastic consistency concrete - MT, for formwork moulding concrete.

2. Materials and methods

2.1. Materials

To study the mixtures, the mortar matrix of the concrete was considered, consisting of binder paste and sand fractions. CEM II-A/L 42.5R (C) was used, as well as F-type fly ash (FA), limestone filler (LF), Cape Verde pozzolans (Poz) and electric furnace slag (Slag) additions, with the following density values in kg/gm^3: 3.08; 2.30; 2.70; 2.30; 3.83, respectively. Since sand has a great influence on the grain size of the mixtures, particularly on packing density and workability, a mixture of fine sand 0/1 mm and medium 0/4 mm sand was used. Two types of admixtures were used: Sikament HE200P, a water reducer for dry concrete with density of 1.17 kg/gm^3, favouring a better dispersion and utilization of cement for the BT dry mixtures; Glenium SKY526, ether-polycarboxylate based superplasticizer with a density of 1.06 kg/gm^3, to increase plasticity and reduce the amount of water for the MT mixtures. The dosage set for each mixture was adjusted to achieve the desired target workability and the set air content.

2.1.1. Mixtures

The two types of mortar matrix mixtures, BT-dry consistency and MT-plastic consistency, were formulated according the proportioning of corresponding concretes, being those presented in Table 1, together with water/binder ratio (W/B) and the compactness of each mixture, and compared with two reference mixtures, BT_ref and MT_ref, which have current design parameters of precast concrete. Compactness is a packing density volumetric ratio between the volume of solid particles and the total volume of con-

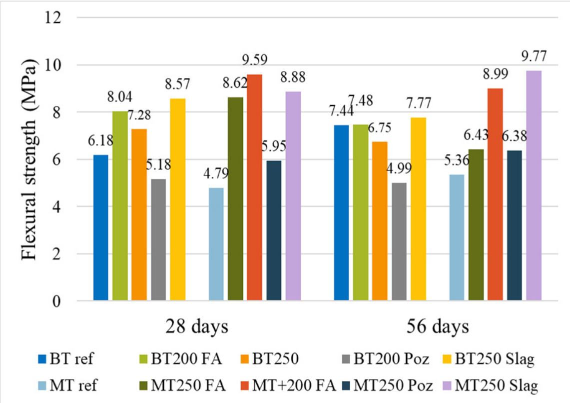

Figure 1. Flexural strength at 28 and 56 days.

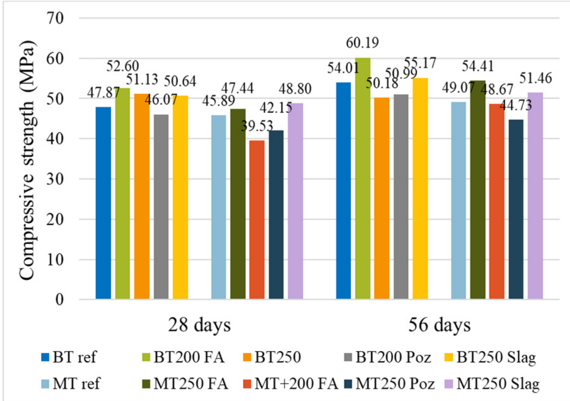

Figure 2. Compressive strength at 28 and 56 days.

crete, which is firstly estimated using the formulation parameters and then controlled by the measured values of density, air content and compacted volume. The air content was targeted to 2.0% in BT and 1.5% in MT mixtures, which corresponds to 3.5% and 2.4%, respectively in mortar matrices.

2.2. Experimental tests

The tests to measure the consistency through spreading and air content of the mixtures, in order to adjust the dosages of the constituents, were performed according to the procedures of EN 1015-3 [7] and EN 1015-7 [8], respectively. Admixtures' dosages were adjusted to achieve the target consistency of each mixture, whose dosage in relation to the weight of cement varied between 29 and 34.8 ‰ in BT and between 7.2 and 10.5 ‰ in MT. The tests to access flexural and compressive strengths on mortars were performed on prismatic specimens ($40 \times 40 \times 160$ mm^3), according to EN 1015-11 [9], and the results were obtained by averaging three specimens for flexural and six half specimens for compressive, at each age (28 and 56 days). Shrinkage was assessed at several ages (1, 3, 7, 14, 28, 56, 90, 120 and 180 days) by the average of three prismatic specimens ($40 \times 40 \times 160$ mm^3) according to EN 1015-13 [10]. The Young's modulus test was performed after a 56-day of curing and followed the standard LNEC E397 [11], using a prismatic specimen of $50 \times 50 \times 300$ mm^3. Capillary water absorption was evaluated by averaging three specimens of $40 \times 40 \times 160$ mm^3 according to the LNEC E393 [12]. The determination of carbonation resistance was assessed according NT Build 357 [13] standard by averaging two specimens of $40 \times 40 \times 80$ mm^3 with 5% of CO_2 at different ages (7, 14, 28, 56 and 90 days). The chloride diffusion coefficient by non-steady state migration was obtained according to the procedure of NT Build 492 [14], at 28 and 56 days, by the average of three specimens per age.

3. Results and discussion

3.1. Mechanical Properties and Shrinkage

3.1.1. Flexural and Compressive Strengths

The results of average strengths at 28 and 56 days, for BT and MT mixtures, are shown in Figure 1 and 2, respectively for flexural and compressive strengths. Both BT and MT formulations, regarding flexural strength, do not tend to evolve from 28 to 56 days, in which minor reductions were registered. Despite the high reduction of cement, several BT mixtures present better performance than the reference, being that improvement even higher in MT. BT250 Slag and MT 250 Slag and MT+200 FA mixtures stands out, since they reach higher values than those of the references, with increases of 39%, 85% and 100%, respectively at 28 days, being those relations similar at 56 days. In compressive strength, for both formulations (BT and MT), the evolution from 28 to 56 days is significant, until 15%, due to pozzolanic effect. Despite the cement reduction, mixtures present similar or higher performance than the references, by increasing packing density and incorporating additions. Mixtures with fly ash and with slag in cement replacement revealed improvements until about 11%, and 6% respectively.

3.1.2. Shrinkage

Evolutions of mortar shrinkage over time are shown in Figure 3, for BT and MT mixtures. In the first type, BT250 mixture (with filler and fly ash additions) and BT200 Slag stands out for its lower shrinkage results, being the shrinkage about 20 to 25% below reference; BT200Poz mixture stands out for having a very high initial shrinkage, which stabilizes after the first month, being the value about 20% superior than reference; the other mixtures of this type present a smoother evolution, stabilizing after 90 days. In MT mixtures, all present lower values (from 20 to 50%) than reference, being MT250 FA and MT250 Slag those with the lowest shrinkage; the evolution of those mixtures tend to stabilize between 28 and 56 days, while reference reaches that point at 120 days.

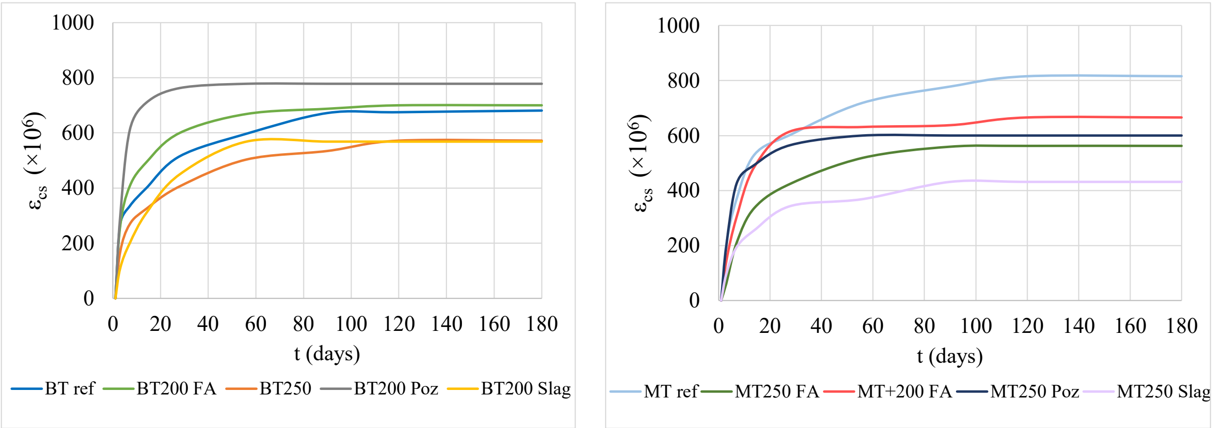

FIGURE 3. Shrinkage evolution of BT (left) and MT (right) mixtures with time.

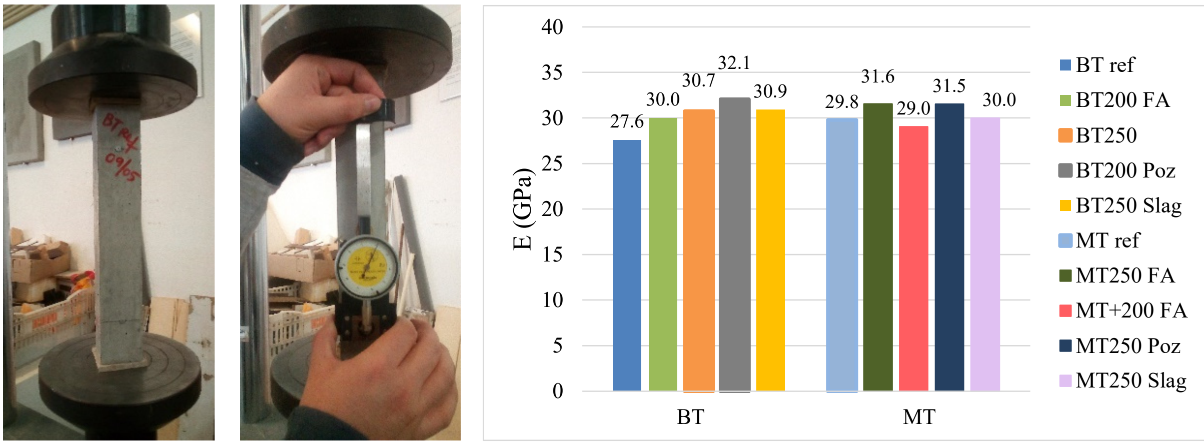

FIGURE 4. Young's modulus test (left) and the values for BT and MT mixtures at 56 days (right).

3.1.3. YOUNG'S MODULUS

The obtained average values for the Young's modulus at 56 days are shown in Figure 4. By analysing the graph, the additions and increasing of packing density is evident in increasing Young's modulus compared to reference, being that increase of 8 to 16% in BT mixtures and until 6% in MT mixtures. Pozzolans, fly ash, and slag additions revealed significant increases, which may have an even higher effect on concrete, since high packing density and coarse aggregates will increase that property.

3.2. DURABILITY

3.2.1. WATER ABSORPTION THROUGH CAPILLARITY

Figure 5 shows the values of capillary water absorption of the BT and MT mixtures. Since the concrete quality of this parameter is considered "high" below $0.1\,\mathrm{mg/mm^2} \times \mathrm{min}^{1/2}$, "average" between 0.1 and $0.2\,\mathrm{mg/mm^2} \times \mathrm{min}^{1/2}$ and "low" above $0.2\,\mathrm{mg/mm^2} \times \mathrm{min}^{1/2}$ [15], it is possible to verify that in BT mixtures, only the BT250 can be considered of medium quality, while the others are well rated. As for MT mixtures, only MT250 Poz and MT250 Slag remain throughout the test in the "high quality" classification. The rest start from being medium quality and acquire a better rating over time. This proves a non-linear behaviour of this parameter, since the evolutions are more compatible with power functions, tending to improve with age by the pozzolanic effect.

By analyzing the results of this test, performed on three consecutive days, it can be concluded that the mixtures with higher packing density, both BT and MT, combined with slag addition present the best results in the evaluation of this parameter, absorbing about 45% less water than the reference in BT mixture and less 60% in MT mixture. Fly ash and pozzolan addition also revealed good performance in reducing water absorption.

3.2.2. CARBONATION RESISTANCE

The analysis of carbonation depth, C_{depth}, of the studied mixtures (Figure 6) proved to evaluated with a linear tendency with square root of time (Figure 7), as expected. It is evident that the amount of cement is highly influent in carbonation resistance; despite the increase of packing density and the replacement of cement by additions, the optimized mixtures revealed in general higher values then the references, until 160% in BT200FA and 95% in MT+200FA. In BT mixtures, this phenomenon is more noticeable since the difference of cement dosage is higher and

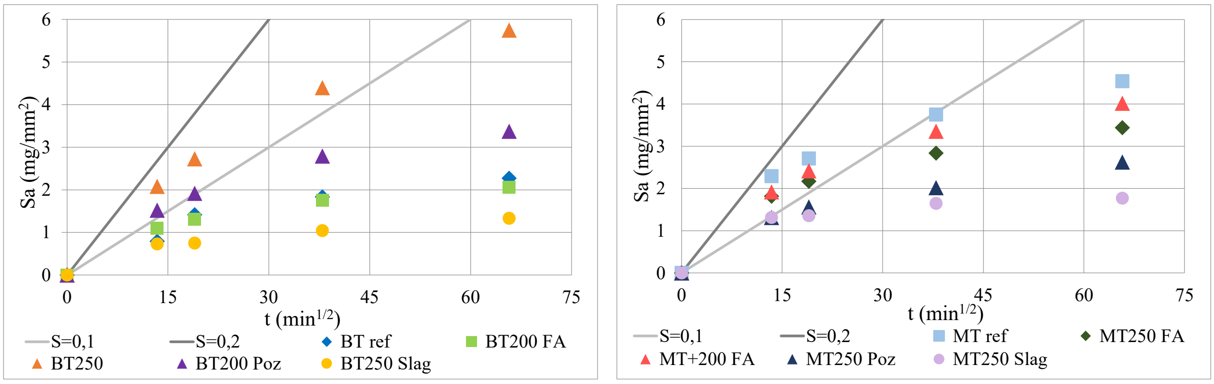

Figure 5. Capillarity water absorption through square root of time of BT (left) and MT(right) mixtures.

Figure 6. Chamber for the carbonation test and evolution of carbonation MT250FA with time.

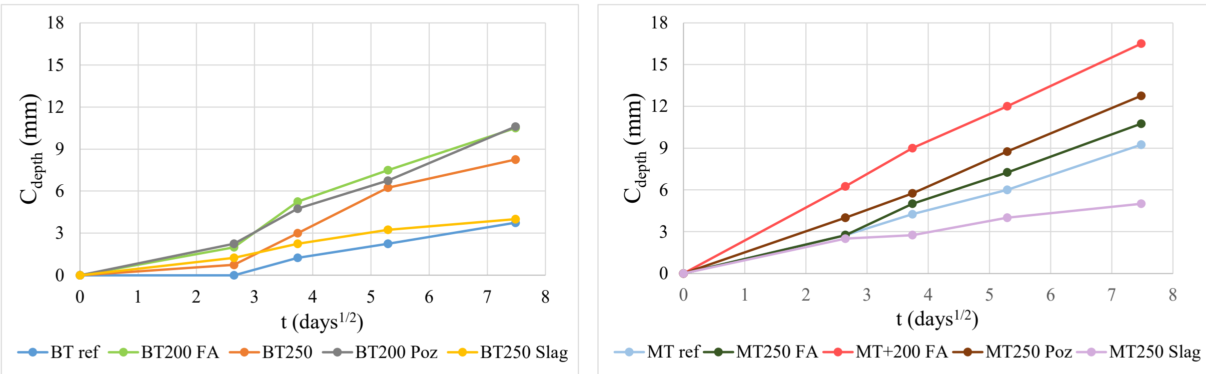

Figure 7. Carbonation depth of BT (left) and MT (right) mixtures.

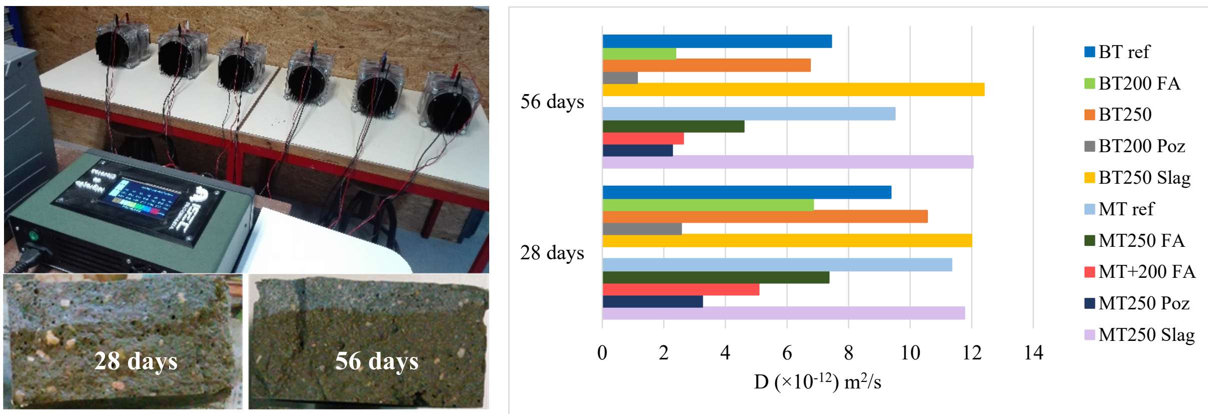

Figure 8. Chloride migration (left) and D coefficient at 28 and 56 days for BT and MT mixtures (right).

the reference shows the best results, followed by mixtures with more cement, BT250 Slag and BT250, although it contains partial substitution by additions. MT mixtures show the same trend, although with a smaller difference from the reference; in those, it is also possible to verify that the increase in the amount of binder replacing cement is harmful to the carbonation resistance, while MT250FA present good resistance, with a carbonation depth similar to the reference. MT250 Slag present a significant reduction (about 30%) in comparison to the reference, proving the ability of slag to increase carbonation resistance.

3.2.3. Chloride migration

The results shown in Figure 8 represent the chloride diffusion coefficient (D) by non-steady state migration test at 28 and 56 days. In this test (Figure 8), as lower is D coefficient as higher is the resistance to chloride migration, being the durability also higher. The graph prove that mixtures improve its results at 56 days, comparing to 28 days, due to pozzolanic effect, in which in most cases this difference is substantial (reduction until near 65% for mixtures with fly ash). Mixtures with pozzolan additions (BT200 Poz and MT250 Poz) have very low D results compared to the others and to the reference, which makes them stand out positively, being the coefficient until 85% and 80% lower than references, respectively. In contrast, mixtures with slag additions (both BT250 Slag and MT250 Slag) show the higher chloride migration, being until about 25% and 60% higher than reference in MT and BT mixtures, respectively; in slag addition does not promote apparent improvement with age, contrarily to the remaining mixtures.

4. Conclusions

From the analysis of the obtained results in the experimental study, regarding the effect of combining the increase of packing density with adding different cementitious supplementary materials in two types of mortar mixture (BT, with dry consistency; MT, with plastic consistency), it was possible to draw the following conclusions:

1. Despite the reductions in cement content (from 30 to 50%), flexural strength increases significantly with different additions up to 100% comparing to reference mixtures, being the flay ash and slag mixtures those with higher strengths.
2. Compressive strength of mixtures with additions tend to increase from 28 to 56 days up to 15% due to pozzolanic effect and, despite the cement reduction, it increases up to 6% and 11% with slag and fly ash, in comparison to references.
3. The replacement of cement by additions promotes a significant decrease in the shrinkage between 20 to 50%, being mixtures with slag and fly ash those with major reductions.
4. Adding eco-efficient supplementary binders (pozzolan, slag and fly ash) increases Young's modulus of mortar matrices up to 16% (mainly in mixtures with dry consistency, BT), comparing to references, being expected to have a higher effect on corresponding concrete, due to the stiffness of coarse aggregates and to high packing density.
5. Capillary water absorption allow to consider all mixtures as high quality, but the mixtures with slag addition promotes high reduction of water absorption compared to references, from 45 to 60%, followed by fly ash mixtures, also with reductions up to 45%.
6. In carbonation resistance, the cement dosage has an important positive influence on reducing carbonation depth, being reference mixtures those with less carbonation; however, mixtures with slag addition have similar or even better effect in reducing carbonation than references.
7. Chloride diffusion coefficient of mixtures with additions proves a high influence of pozzolanic effect and the corresponding maturity of the matrices with age, since chloride migration reduce until 65% from 28 to 56 days of age; the additions of fly ash and of pozzolans are very advantageous for resistance to chloride migration, being the latter the best, since it reduces the chloride coefficient by 80 to 85%; contrarily, slag addition proves a different effect on tested mixtures, since it increases the chloride coefficient from 25 to 60% in comparison to references, and it does not improve with age.

Overall, the evolution of conventional cementitious mixtures to eco-efficient mixtures with less cement and addition does not decrease the performance of materials, on the contrary, depending on the additions, it may result in significant improvements of the mechanical, time dependent and durability performances of concrete mixtures.

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