TÉCNICO LISBOA

Performance of mortars with fine recycled aggregates and magnesium oxides as partial cement substitution

Tiago Miguel Cleto Gonçalves

Master Thesis in Civil Engineering

Extended Abstract

Supervisors

Professor Doctor Jorge Manuel Caliço Lopes de Brito

Doctor Rui Vasco Pacheco Santos da Silva

Jury

President: Professor Doctor Albano Luís Rebelo da Silva das Neves e Sousa

Supervisor: Professor Doctor Jorge Manuel Caliço Lopes de Brito

Members: Professor Doctor Miguel Nuno Caneiras Bravo

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1 Introduction

The Construction sector is responsible for the production of a huge amount of waste (CDW) both in Portugal and in the rest of Europe. In order to prevent and to reduce the amount of CDW, the Portuguese directive 46/2008 (March 12th), altered by the directive 73/2011 (June 17th), establishes that procedures such as the separation or the valorisation of these materials is necessary. These operations, besides allowing the reduction of the environmental impact of CDW caused by landfill, also contribute to the decrease in the emission of gases and in the energy necessary to produce natural aggregates (NA), as well as to the reduction of the extraction of natural resources. Therefore, according to Silva *et al.* (2016), in addition to being more sustainable than their landfill, the reutilisation of CDW can also create new business markets.

Shrinkage is one of the most detrimental parameters to the performance of concrete or of mortars. In fact, cracks can significantly reduce the performance of these materials, or even their durability. Therefore, it is important to define alternatives to reduce the influence of this parameter on the performance of those materials. According to Du (2005), the investigation of magnesium oxides (MgO) as concrete or mortars binder was triggered by the discovery, during the construction of the Baishan dam (China) in the 60's and 70's, that the use of these oxides allows the decrease of cracking. This decrease results from the expansion of MgO's particles when hydrated, since the volume of its hydration products increases by 117% (June, 2005). Regarding its environmental impact, Ruan and Unluer (2016) point out that the total emissions associated to the production and use of MgO's is up to 50% less than those associated to Portland cement (PC) production.

This research relies on these two concepts. With the substitution of fine natural aggregates (FNA) with fine recycled aggregates (FRA) and the partial cement substitution with MgO (as binder) in mortars, new alternatives that permit a decrease in the environmental impact of the Construction sector are analysed; in addition, the viability of the incorporation of more sustainable materials than cement in the performance of mortars is also studied.

2 Experimental campaign

The main objective of this research is to study the influence of FRA as FNA substitution (up to 4 mm) and MgO as partial cement substitution on mortars' performance. Besides that, a comparative analysis on the use of two different types of MgO in their performance is also carried out.

The FNA substitution is done at three distinct levels (0%, 50% and 100%), whereas the partial cement substitution is done at four distinct levels: 0%, 10%, 15% and 20% (by weight of cement).

All mortars have a volumetric ratio of 1/3 (binder/aggregates) and a water/binder ratio of 0.5, approximately. Since their composition is similar to the concrete's, except for the absence of coarse aggregates, the analysed mortars can be considered as the mortar phase of concrete.

2.1 Materials

The materials used in this experimental campaign were: sand (fine and coarse); cement CEM I 42.5R; FRA (up to 4 mm); and MgO. The characteristics of ARF original concrete are presented in Table 1. The two different MgO used are considered light-burned MgO (because of their calcination temperature) and their characteristics are presented in Table 2.

Table 1 - Original ARF's concrete's characteristics

Concrete's characteristics	Classification
Resistance class	C 30/37
Environmental exposure class	X0
Chloride content	CL 0.40
Maximum aggregates' dimension (mm)	22
Consistency class	S2

Table 2 - Chemical composition of the two MgO used

Element	MgO A	MgO B
C (%)	5.4	7.9
O (%)	33.1	35.3
Mg (%)	47.2	49.4
Ca (%)	3.9	2.9
Cu (%)	2.2	2.5

While MgO A comes from Austria and is supplied by Styromag company, MgO G originates from Greece and is supplied by Grecian Magnesite S.A. All test comparisons used MgO A and other materials, because the use of this oxide always leads to better results than the Greek one.

2.2 Procedures

The experimental campaign was organized in distinct subphases, which were related to the aggregates used and to the mortars both in fresh state and in hardened state.

All tests were executed taking into account European standard specifications in order to allow comparability with other studies.

3 Results and discussion

3.1 Aggregates

3.1.1 Particle size distribution

Several particle size distributions of fine sand, coarse sand and FRA were determined.

Since it was important to maintain the aggregates' particle size distribution constant during the FNA replacement, and also because FRA will replace 50% of each type of sand (coarse and fine), the best FRA's particle size distribution was adapted to become similar to that mixture of 50% of each type of sand - Tables 3 and 4.

Table 3 - Percentage of 50% mixture's material retained

Sieves (mm)	Particle size distribution (50%-50%) (%)
16 - 8	0.05
8 - 4	1.35
4 - 2	6.15
2 - 1	15.55
1 - 0.5	26.30
0.5 - 0.25	35.10
0.25 - 0.125	14.05

Table 4 - Percentage of material retained adopted in FRA's particle size distribution

Sieves (mm)	FRA's particle size distribution adopted (%)
8 - 4	0.00
4 - 2	6.80
2 - 1	15.80
1 - 0.5	26.50
0.5 - 0.25	35.30
0.25 - 0.125	14.20
0.125 - 0.063	1.40

3.1.2 Bulk density and apparent bulk density

The bulk density results are presented in Table 5. The apparent bulk density results are presented in Tables 6 and 7.

Table 5 - Aggregates' bulk density results

Material	Bulk density (kg/m^3)		
	ρ_a	ρ_{rd}	ρ_{ssd}
Fine sand	2620	2604	2610
Coarse sand	2629	2611	2618
FRA	2535	2143	2298

Table 6 - Material's apparent bulk density

Material	Apparent bulk density (kg/m^3)
Fine sand	1560
Coarse sand	1634
MgO A	652
MgO G	618
Cement	1040

Table 7 - FRA's particle size distribution

FRA's particle size distribution (mm)	Apparent bulk density (kg/m^3)
4-2	1144
2-1	1167
1-0.5	1162
0.5-0.25	1220
0.25-0.063	1129

3.1.3 Water absorption

The 24 hour results concerning the fine sand, coarse sand and FRA were 0.233%, 0.250% and 6.010%, respectively. Moreover, the FRA 10 min. result was 86% of its total water absorption.

3.2 Mortars' properties in the fresh state

3.2.1 Workability

Since the studied mortars can be considered as the mortar phase of concrete, 200 $\pm$ 15 mm was adopted as the target workability. All mortars presented workability values within this range except for the reference mortar (A-0-0), which, due to its water/binder ratio of 0.5, presented a value of 232 mm.

These test results show an increase in the amount of water needed to maintain the target workability as the FRA's percentage increased. Silva *et al.* (2014) justify this trend with the FRA's greater capacity to absorb water and their greater angularity. A similar trend was observed for MgO by Tran and Scott (2016), who stated that it is caused by the greater angularity and roughness of the MgO's particles.

In mortars that have simultaneous incorporation of FRA and MgO there is no superimposition of the effects, that is, there is no linear variation between the FRA's and MgO's incorporation percentage and the amount of water necessary to maintain the target workability.

Comparing the two types of MgO used, it is found that the Greek MgO (G) incorporation causes a decrease in workability. This decrease may be caused by the difference between the specific surface areas of both oxides. Therefore, the greater the specific surface area of the MgO, the lower its workability, since a larger quantity of water is necessary to cover all the material particles' area.

3.2.2 Bulk density

The results presented in Figure 1 show a decrease in mortars' bulk density with the increase of FRA replacement. This trend is similar to what Silva *et al*. (2014) and Corinaldesi and Moriconi (2009) reported in their researches, and the major justification for it is the FRA's lower apparent density, since it has original binder paste adhered.

There is no significant change with the increase of the MgO's incorporation percentage. The same can be pointed out in the comparison between the two types of MgO used. These two trends may be caused by the lower difference between the MgO's and the cement's bulk density.

3.3 Mortars' properties in the hardened state

3.3.1 Modulus of elasticity

Mortars that incorporate FRA, the results of which are presented in Figure 2, show a decrease in the modulus of elasticity with the increase of the FNA's replacement. This trend is in agreement with the results of Khatib's (2004) and Evangelista and de Brito (2007). These authors explain this decrease with the mixtures' porosity increase, caused by the incorporation of FRA, and with the FRA's lower bulk density (which causes less dense mortars and, consequently, more susceptible to cracking).

Figure 3 shows a slight decrease in the mortars' modulus of elasticity with the Austrian MgO's percentage increase. Although this decrease is not significant, it could be influenced by the porosity increase due to the incorporation of MgO. Choi *et al*. (2014) mention that the use of MgO should not significantly change the mortars' porosity, but the MgO's percentage used by these authors (5%) is clearly lower than the percentage in this research.

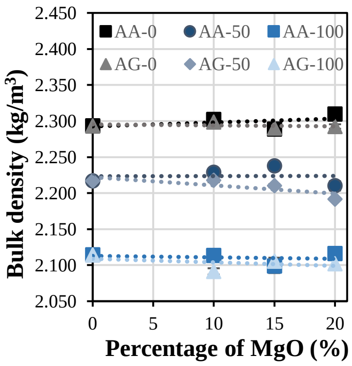

Figure 1 - Bulk density of all mortars

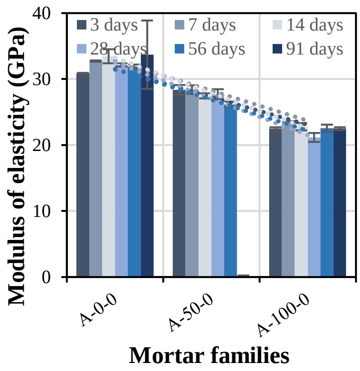

Figure 2 - Relationship between the modulus of elasticity and the FRA's percentage

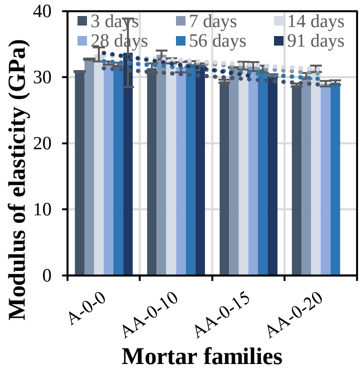

Figure 3 - Relationship between the modulus of elasticity and the Austrian MgO's percentage

The simultaneous incorporation of MgO and FRA (Figures 4, 5 and 6) resulted in a greater decrease in the modulus of elasticity when compared to mortars that had just one of the two materials incorporated. Therefore, there was a superimposition of the effects.

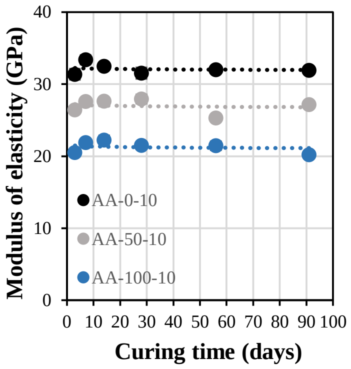

Figure 4 - Modulus of elasticity of mortars with 10% of MgO incorporated

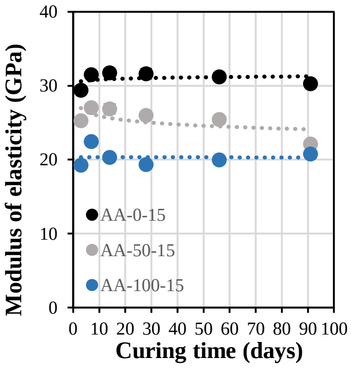

Figure 5 - Modulus of elasticity of mortars with 15% of MgO incorporated

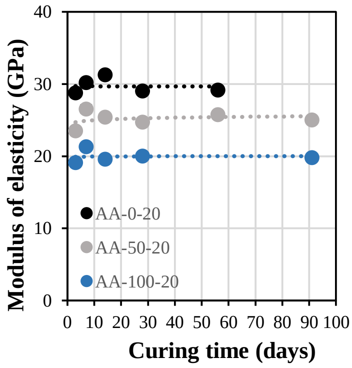

Figure 6 - Modulus of elasticity of mortars with 20% of MgO incorporated

In regard to the comparison between the two MgO's results, mortars that incorporate Greek MgO exhibited lower modulus of elasticity than those with Austrian MgO (Figure 7). This can be due to Greek MgO's lower granulometric extension and higher w/b ratio of the corresponding mortars.

3.3.2 Flexural and compressive strength

Both tests of flexural and compressive strength were repeated at 3, 7 14, 28, 56 and 91 curing days. The flexural strength results of mortars that incorporate FRA and Austrian MgO are presented in Figures 8 and 9, respectively. The compressive strength results of mortars that incorporate FRA and MgO are presented in Figures 10 and 11, respectively. The results show the same trend in both materials, that is, there is a decrease in flexural and compressive strength with the increase of Austrian MgO's and FRA's percentage.

The FRA's incorporation results are in agreement with Zhao *et al*. (2015), and these authors ascribe them to the existence of original binder paste adhered to FRA (which increases its porosity thereby causing a less dense mortar).

According to Mo *et al*. (2015), the Austrian MgO mortars' trend can be explained by the decrease in cement content in the mortars' composition. Since the MgO's hydration products are less resistant than the cement ones, the greater the MgO's percentage as partial cement substitution, the greater the decrease in mortars' strength (comparing with the reference mortar).

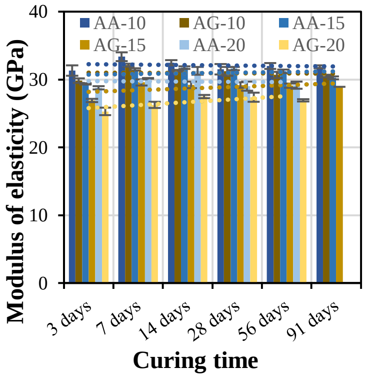

Figure 7 - Comparison between the modulus of elasticity of mortars with two types of MgO

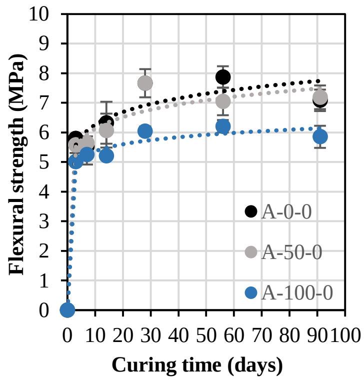

Figure 8 - Flexural strength over time of mortars with FRA

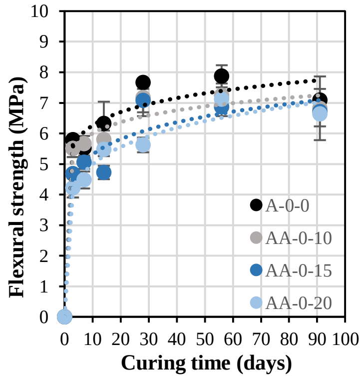

Figure 9 - Flexural strength over time of mortars with Austrian MgO

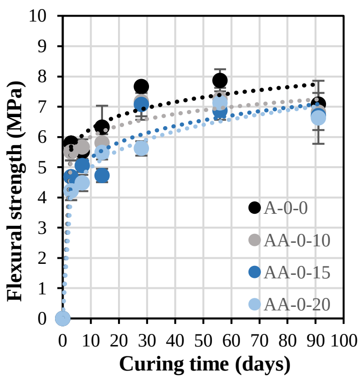

Figure 10 - Compressive strength of mortars with FRA, over time

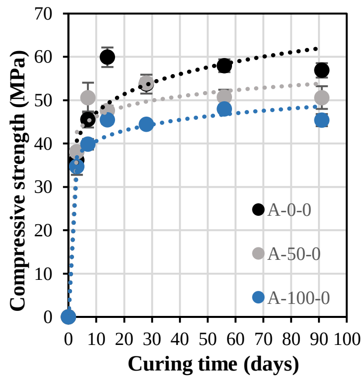

Figure 11 - Compressive strength of mortars with Austrian MgO, over time

The simultaneous incorporation of Austrian MgO and FRA results are presented in Figures 12, 13, 14 and 15. The simultaneous incorporation of the two materials causes a superimposition of the effects, that is, since the individual incorporation of each material negatively influences the mortars' performance, the simultaneous incorporation causes an even higher decrease.

Regarding the comparison between the two MgO, Figures 16 and 17 show a higher initial strength increase in mortars that incorporate Austrian MgO, probably due to the lower quantity of water used in its production. Over time, the difference between the strength of the two types of mortar decreases.

3.3.3 Carbonation

The results of mortars that use FRA (Figure 18) show an increase in carbonation depth with the increase of FNA's replacement. These results are in agreement with Evangelista and de Brito's (2010) conclusions. The main cause of this trend is the increase in porosity caused by the use of FRA. This porosity increase makes the CO_2 diffusion easier and, consequently, facilitates the carbonation of the material.

Figure 19 also shows the increase in depth carbonation with the increase of Austrian MgO's percentage. This is not what Choi *et al*. (2014) and Mo e Panesar (2012) concluded, as these authors maintain that the use of MgO as binder showed advantages in carbonation. One of the reasons for this difference of results could have been the difference between the MgO's replacement ratios used.

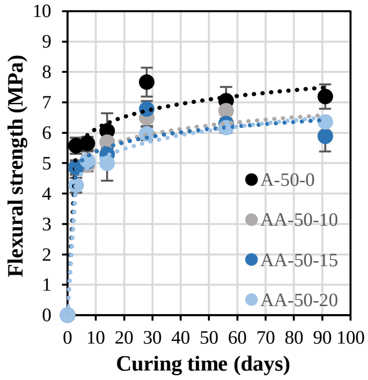

Figure 12 - Flexural strength of mortars with 50% of FRA

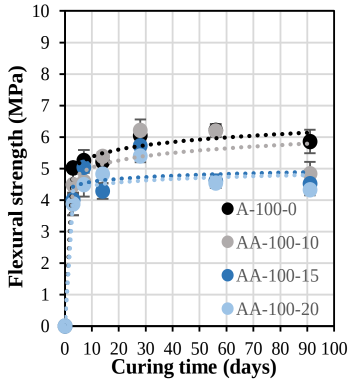

Figure 13 - Flexural strength of mortars with 100% of FRA

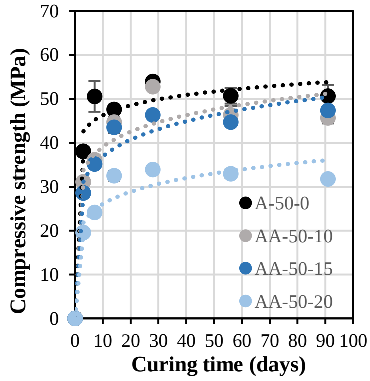

Figure 14 - Compressive strength of mortars with 50% of FRA

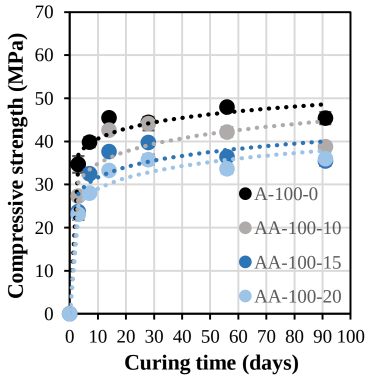

Figure 15 - Compressive strength of mortars with 100% of FRA

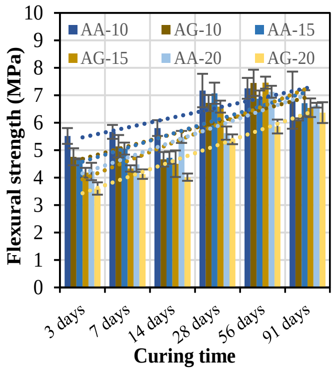

Figure 16 - Comparison between the flexural strength of mortars that use each type of MgO

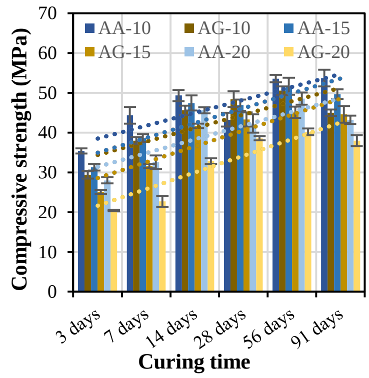

Figure 17 - Comparison between the compressive strength of mortars that use each type of MgO

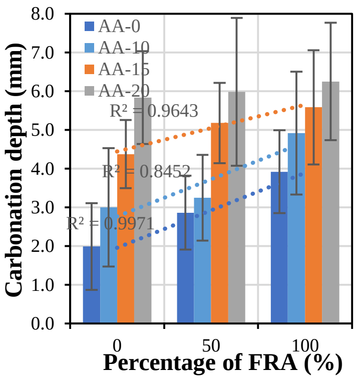

Figure 18 - Relationship between mortars' carbonation depth and FRA's percentage, at 91 curing days

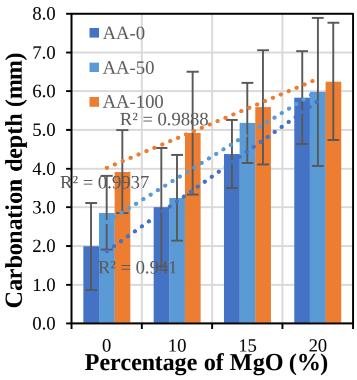

Figure 19 - Relationship between mortars' carbonation depth and Austrian MgO's percentage, at 91 curing days

The results of the use of the two types of MgO are presented in Table 8. These results show a similar behaviour between the two mortar families.

3.3.4 Shrinkage

The main reason to study the use of MgO as binder in mortars or concrete is its theoretical ability to expand when hydrated.

The shrinkage results of mortars that use FRA and Austrian MgO are presented in Figures 20 and 21, respectively. While Figure 20 shows an increase in mortars shrinkage with the increase of FNA's replacement, Figure 21 shows the opposite trend.

Table 8 - Carbonation depth of mortars that use each type of MgO, at 91 curing days

MgO types	**Austrian (A)**		**Greek (G)**	
Family	*Average (mm)*	*Standard deviation (mm)*	*Average (mm)*	*Standard deviation (mm)*
AA/AG-0-10	3.00	1.53	2.04	1.07
AA/AG-0-15	4.38	0.88	4.13	1.38
AA/AG-0-20	5.83	1.20	-[NA]	-[NA]
AA/AG-50-10	3.25	1.11	3.64	1.20
AA/AG-50-15	5.10	1.04	4.17	1.21
AA/AG-50-20	5.99	1.91	5.49	1.67
AA/AG-100-10	4.92	1.59	4.72	1.33
AA/AG-100-15	5.58	1.48	5.56	1.82
AA/AG-100-20	6.25	1.52	5.82	1.23

NA The test was not executed or an experimental error occurred

The FRA's trend is caused, according to Neno *et al*. (2014), by the greater recycled aggregates' porosity, which leads to a reduced stiffness of the mortar and, consequently, to one that has more tendency to emphasize the cement's shrinkage.

The MgO results are in agreement with the studies of Gao *et al*. (2013) and Mo *et al*. (2012). The main reason for the shrinkage decrease, relative to the reference mortar, is the ability that MgO's particles have to expand when hydrated. Therefore, MgO's hydration products, namely brucite, have a greater volume than their reagents.

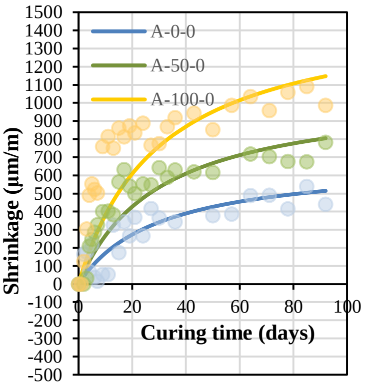

Figure 20 - Shrinkage of mortars that use FRA

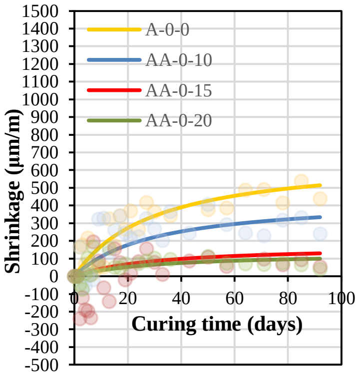

Figure 21 - Shrinkage of mortars that use Austrian MgO

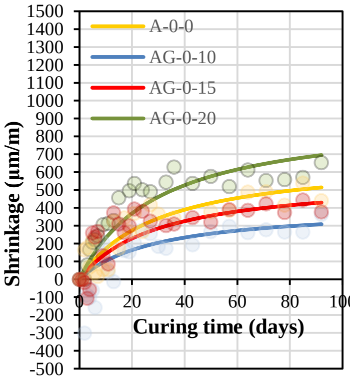

Figure 22 - Shrinkage of mortars that use Greek MgO

The simultaneous use of MgO and FRA results in an overlap of the effects. This means that, although the use of FRA increases mortars' shrinkage, this one will decrease as the MgO's percentage increases.It is important to mention that part of the shrinkage's decrease is due to the reduction of cement's quantity. The increase in the MgO's percentage results in a decrease in the cement's quantity and, consequently, in a decrease in the cement's autogenous shrinkage.

All mortars that use MgO expand in the first curing days. This initial expansion is caused by MgO's high reactivity. Therefore, the MgO's high reactivity offsets the initial cement's shrinkage, leading to an expansion.

Regarding the shrinkage of mortars that use Greek MgO, the results are presented in Figure 22. They are not similar to Austrian MgO results because there is only a linear trend between their shrinkage and the Greek MgO's percentage up to 10% of MgO. This variation of results can be due to the reactivity of each oxide. The greater reactivity of Austrian oxide can lead to a higher hydration at 91 curing days. Hence, lower particles hydration results in a lower expansion, since it is the brucite's formation ($Mg(OH)_2$) that causes the volume increase.

3.3.5 Water absorption by capillarity

Like carbonation, water absorption by capillarity is influenced by the porosity of the material. Figure 23 presents the capillarity absorption's coefficient of mortars that incorporate FRA. It shows an increase in that coefficient with the increase of FRA's percentage and, according to Fan *et al*. (2016), that is due to the FRA's greater capacity to absorb water when compared to FNA.

In Figure 24, the A-50-0's absorption coefficient stands out. Considering the value of its standard deviation, it can be concluded that, although this mortar's coefficient is higher than the average of the other mortars (for 50% of FRA), statistically speaking, this coefficient could get values quite lower than the other families' one, since its standard deviation has a wide range.

Therefore, in the general analysis, there is an increase in the water absorption's coefficient with the Austrian MgO's percentage increase. These results are not in agreement with what was expected, since, according to Mo e Panesar (2012) and Choi *et al*. (2014), the use of MgO leads to a reduction of the mixtures' porosity. So, the use of Austrian MgO would be expected to cause a decrease in water absorption by capillarity of the studied mortars. However, as pointed out earlier, the MgO's percentage used in this research is significantly higher than that in those studies.

As shown in the carbonation results, mortars that use the two types of MgO analysed show a similar behaviour in water absorption - Figure 25.

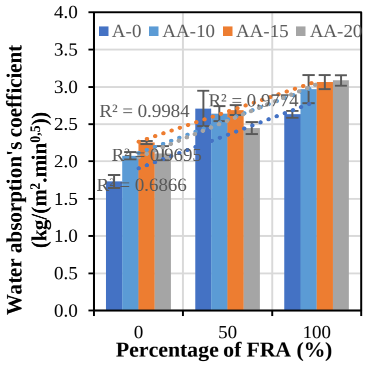

Figure 23 - Relationship between the water absorption coefficient and the FRA's percentage used, between 10 and 4320 min.

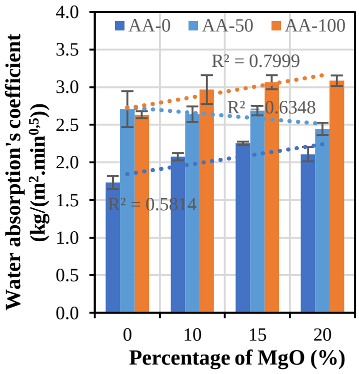

Figure 24 - Relationship between the water absorption coefficient and the Austrian MgO's percentage used, between 10 and 4320 min.

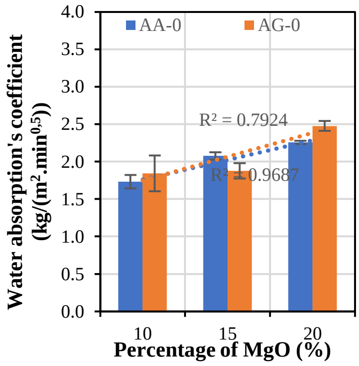

Figure 25 - Relationship between the water absorption coefficient and the percentage of the two types of MgO used, between 10 and 4320 min.

4 Conclusions

Considering the results of all the tests executed, all mortars that incorporate MgO or FRA (or even the two materials simultaneously) have presented a decline in performance when compared with the reference mortar. Comparing the two types of MgO analyzed, the Austrian oxide presented, mostly, better results than the Greek one.

Tables 9 and 10 present a summary of the comparison between all mortars' and the reference mortar's results. Mortars that incorporate FRA have a significantly worse general performance than the reference mortar. In fact, the results show an increase in this difference between mortars with the increase of FRA's percentage. The behaviour was a result of the FRA's higher capacity to absorb water, its lower stiffness, and its original binder paste adhered. All these factors lead to mortars with more porosity and less stiffness, which causes an increase in their carbonation, water absorption by capillarity and shrinkage. Furthermore, higher quantities of water were required to maintain constant workability levels, which also negatively affected their strength and modulus of elasticity.

Table 9 - Comparison between the results of mortars with MgO A and G and the reference mortar

Mortars (0% of FRA)	**MgO A**			**MgO G**		
Tests	*10%*	*15%*	*20%*	*10%*	*15%*	*20%*
Workability (cm)	=	-	-	-	-	-
Bulk density (kg/dm³)	=	=	=	=	=	=
Modulus of elasticity (91 curing days) (GPa)	=	=	- NA	=	-	- NA
Flexural strength (91 curing days) (MPa)	=	=	=	-	=	=
Compressive strength (91 curing days) (MPa)	=	-	-	-	-	-
Carbonation (91 curing days) (mm)	-	-	-	-	-	- NA
Water absorption by capillarity (kg/(m².min^0,5))	-	-	-	-	-	-
Shrinkage (µm/m)	+	+	+	+	+	-

NA The test was not executed or an experimental error occurred

Table 10 - Comparison between the results of mortars that incorporate MgO A and FRA and the reference mortar

Mortars (with MgO A)	**50% of FRA**				**100% of FRA**			
Tests	*0%*	*10%*	*15%*	*20%*	*0%*	*10%*	*15%*	*20%*
Workability (cm)	-	-	-	-	-	-	-	-
Bulk density (kg/dm³)	=	=	=	=	=	=	=	=
Modulus of elasticity (91 curing days) (GPa)	- NA	-	-	-	-	-	-	-
Flexural strength (91 curing days) (MPa)	=	-	-	-	-	-	-	-
Compressive strength (91 curing days) (MPa)	-	-	-	-	-	-	-	-
Carbonation (91 curing days) (mm)	-	-	-	-	-	-	-	-
Water absorption by capillarity (kg/(m².min^0,5))	-	-	-	-	-	-	-	-
Shrinkage (µm/m)	-	-	+	=	-	-	+	+

NA The test wasn't executed or occurred an experimental error

Caption:

" = " Behaviour similar to the reference mortar (variation up to 10%)

" - " Behaviour is worse than the reference mortar

" + " Behaviour is better than the reference mortar

Mortars that incorporate MgO have a worse general performance than the reference mortar. Although their values are not so reduced as FRA's, they have several parameters that are not adequate for materials with their kind of requirements. The main reasons for their performance decrease are the lower strength of MgO's hydration products, and their porosity increase. These factors lead to mortars with less strength and higher carbonation depth. The great advantage of the use of MgO is the shrinkage's reduction, which is caused by the MgO's ability to expand when hydrated. Comparing the results of the two types of MgO, there is a significant decrease in some Greek MgO's parameters in relation to the Austrian MgO's ones. Even the shrinkage results of mortars that incorporate Greek MgO are worse than those with Austrian MgO.

In conclusion, although all mortars have a worse behaviour than the reference one, the incorporation of only 10% of Austrian MgO leads to reasonable results. Despite a decrease in compressive strength and an increase in carbonation and water absorption by capillarity, in the remaining tests the mortar that incorporates this amount of oxide had a similar behaviour, or even a better one (for example, in shrinkage) than the reference one. The use of 15% of Austrian MgO had reasonable results too, although they were slightly worse than the 10% one. The use of FRA did not reach satisfying results considering the performance requirements for this type of material. Its use could possibly be viable in mortars with fewer requirements than the ones in this research.

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