Section A-Research paper
ISSN 2063-5346

Experimental Investigations on Concrete with replacement of cement by reactive magnesium oxide and fly ash

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doi: 10.31838/ecb/2023.12.si6.292

Abstract: The durability performance of sustainable concrete that included reactive magnesium oxide (MgO) and fly ash (FA) was assessed in this study. Due to the sustainability advantages and decreased shrinkage, the partial substitution of cement with these two materials is an intriguing alternative for the building industry. The percentages of FA incorporation by partial cement replacement were 0%, 15%, and 30%. MgO was added to concrete at different rates: 0%, 5%, 10%, and 20%. There were two different kinds of MgO utilised, one from Spain and the other from Australia. A comparison of these two materials' individual incorporations was made, and subsequently a comparison of their simultaneous usage was made. In all tests (water absorption through capillarity and immersion, carbonation depth, and resistance to chloride penetration), performance reductions ranging from 3% to 95% were found. Due to the gradual hydration of these two alternative materials, the performance gap between them and the reference concrete tends to narrow with time. It was discovered that the adverse effects did not overlap in the majority of the experiments. In other words, the performance losses brought on by the simultaneous integration of MgO and FA were less than the total of the losses brought on by each component's incorporation separately.

Keywords: concrete; MgO; fly ash; durability properties

1. Introduction

In recent decades, the world's population has been growing tremendously. An rise in housing stock and infrastructure, particularly in major cities, will be one effect of this population growth.

The proper housing of this vast population of people will be made possible by the building sector. 10% of the CO2 generated worldwide is emitted by the same industry. More specifically, the manufacturing of cement contributes 7.4% of CO2. These findings demonstrate that producing concrete has a significant ecological impact [1]. By utilising them as a carbon dioxide collection, utilisation, and storage technique, special mortars can help mitigate the effects of climate change [2]. Several solutions have been put up in an effort to lessen this impact, including the one that will be discussed in this study [3]. In order to solve this issue, mineral admixtures might be used in the manufacture of concrete. In this study, the application of fly ash and MgO was investigated. Concrete cracking can affect the durability of the material and the security of the constructions. This is a particular challenge in locations with extreme weather or significant traffic since continual exposure to environmental stresses weakens concrete. The high alkalinity of the mix, which can lead to the corrosion of reinforcing steel and consequent structural damage, is another issue with Portland cement concrete.

Since reinforcing is necessary for the structural integrity of concrete structures, this issue has caused worry in the construction industry for a number of decades. Researchers have been investigating the use of fly ash and active magnesium oxide as partial substitutes for Portland cement to solve these issues. With regard to MgO, concrete may be made by including it, lowering CO2 emissions [4]. For two main reasons, using reactive MgO as a partial substitute for Portland cement in concrete can cut down on CO2 emissions. Since the manufacturing of Portland cement requires heating raw materials, including limestone and clay, to temperatures of roughly 1450 °C, the first one is the lower calcination temperature. Large volumes of CO2 are released into the atmosphere during this process. Reactive MgO, in contrast, can be created at considerably lower temperatures, usually about 750 C, which results in substantially reduced CO2 emissions [5-7]. This decrease might be explained by carbonation, which is the process by which concrete gradually absorbs CO2 when exposed to the environment. As MgO combines with CO2 to generate magnesium carbonate, using reactive MgO can speed up this process. The carbon emissions connected to the manufacture of Portland cement are partially mitigated by this reaction. The MgO employed in this experiment was light-burned, which exhibits strong reactivity due to its calcination temperature of between 700 and 1000 C [5]. These temperatures are quite modest when compared to the 1450 C required to produce Portland cement [6,7].

Much of the MgO utilised in industry, according to Jin and AL-Tabbaa [5], is created by the calcination of MgCO3, as shown in Equation (1), according to Kramer and Shand [8,9] and Jin and AL-Tabbaa [5].

$$MgCO_3 + \text{heat} \Rightarrow MgO + CO_2 \qquad (1)$$

Mo et al. [10] stated that in the hydration reaction of MgO brucite, $Mg(OH)_2$, is obtained as the end product (Equation (2)).

$$MgO + H_2O \Rightarrow Mg(OH)_2 \qquad (2)$$

More details on the hydration of magnesium oxide were provided by Du [11]. The author claims that because the hydration products of MgO have a higher volume than the reactants,

the creation of brucite results in expansion in concrete. The utilisation of MgO requires a variety of properties, one of which is reactivity. The MgO reaction with water and diluted acids is used to test this attribute, and the reactivity is largely dependent on the material's physical properties and purity. MgO's reactivity tends to rise when its specific surface area and particle size decrease and increase, respectively. The manufacturing circumstances, such as raw material purity and calcination temperature, regulate these two parameters [12].

A MgO sample's hydration happens more slowly the lower its reactivity. The particles in a sample cluster together more due to the decreased specific surface area, which results in less hydration. The same findings were found by Mo et al. [5,10], Al-Tabba, and Jin. Porosity is among the most significant features of concrete. Numerous research have previously been done due to its importance. Cement pastes containing MgO were examined for porosity by Mo and Panesar [13]. MgO concentrations ranged from 0% to 40%. The researchers discovered that when compared to the reference cement paste under rapid carbonation, adding 20% MgO might result in a 32% reduction in pore volume at 28 days. The same findings were achieved by Liu et al. [15], who found that using 5% MgO instead of OPC in mortar manufacture resulted in a 19% increase in porosity after 91 days when compared to the reference mortar. Several investigations on cementitious materials that include MgO have been done. The results reached by the many authors on durability were very obvious. Bravo et al.'s [16] analysis of the capillary water absorption in mortars containing 5%, 10%, 15%, 20%, and 25% MgO in their composition. According to the authors, compared to the reference mortar, water is absorbed through capillarity more readily the more MgO is present. In fact, the worst outcomes were found when 25% MgO was added, with an increase in absorption of nearly 44%.

The water absorption capacity of concrete with the addition of 5% and 10% MgO, together with FA and metakaolin, as a replacement for OPC, was examined by Mavroulidou et al. [17] at a 28-day age. It was discovered that adding 5% MgO reduced the amount of water that could be absorbed. This was ascribed to the fact that higher concentrations of MgO and metakaolin in the mix compacted better because more water was needed to keep the composition consistent. However, greater results were obtained than those shown for the reference concrete with the inclusion of 10% MgO, but poorer results were obtained than The carbonation capability of concrete containing 10% MgO at 14 days was examined by Pu and Unluer [18]. The carbonation depth in specimens containing MgO was twice as deep as that in the reference concrete, according to the authors. According to Gonçalves et al. [19], the same results, noting that the proportion of MgO increased along with a rise in the carbonation depth in mortars. In actuality, depending on the reactivity of the MgO employed, the presence of 20% MgO in the manufactured mortars enhanced the carbonation depth by 139% to 483% at 91 days.

Fly ash is used in an intriguing way since it may be recycled. SiO2 and Al2O3 make up the bulk of this substance. The fly ash employed in this experiment is class F, according to the American Society for Testing Materials [20], since it contains more than 70% SiO2 + Al2O3 + Fe2O3 (silicate + alumina + iron oxide). Physically, a filler effect can be seen, which fills the spaces between Portland cement particles with fly ash particles since they are smaller in size [4]. There is a rise in calcium silicate hydrate (C-S-H), which provides benefits in terms of durability, as a result of the existence of siliceous compounds, which in the presence of

water can be connected to calcium hydroxide [21,22]. Fly ash has a delaying effect on concrete hydration for the first 24 hours. This happens because the ash must solubilize the glassy portion in order for it to interact with the calcium hydroxide. On the surface of the fly ash particles, hydrate development starts to take place after 28 days. In order to make up for the lower degree of hydration at the start of curing, the degree of hydration can rise up to 16% [23].

When compared to reference concrete at 28 days of age, Saha [24] showed that the capillary water absorption in concrete with 10%, 20%, 30%, and 40% FA was reduced by 4%, 13%, 29%, and 32%, respectively. The study found that FA concrete lost its ability to absorb water through capillaries for two different causes. First, FA has more surface area per unit volume than cement, and second, FA thins the interfacial transition zone (ITZ) between aggregates and binders. According to Nayak et al. [25], concrete with 40% FA had water absorption rates by immersion and capillarity that were 26% lower than those of reference concrete. This is likely because of the concrete's enhanced reactivity with the chemicals generated during the hydration process. Again, Saha [24] came to the conclusion that the chloride penetration after 28 days was decreased by 3%, 27%, 48%, and 53%, respectively, compared to the reference concrete in concrete with 10%, 20%, 30%, and 40% FA. According to the study, the fineness of fly ash is to blame for this drop. Another explanation for this superior behaviour, according to [27], is the reduced concentration of alkali ions (Na+ and K+) and related hydroxyl ions (OH) in the pore solution.

According to Sadrmomtazi et al. [28], concrete containing FA had more chloride penetration at 28 days than control concrete did. On the other hand, the application of FA at the age of 90 days reduced the chloride penetration by up to 30% as a result of the development It was feasible to determine through studying the interaction of fly ash and MgO that MgO is insoluble with C-S-H due to the hydration of Portland cement and fly ash. In order to create hydrated magnesium silicate (M-S-H), brucite will react with the silica in fly ash [32]. Brucite and M-S-H are two possible byproducts of the hydration of MgO, depending on the quantity of silica present. In their investigation, Choi et al. [33] concentrated on concrete that had FA and MgO partially incorporated. For the experimental campaign, they added 20% FA to all mixtures while varying the MgO content from 0% to 5%. The specimens underwent 28 and 360 days of water curing. Different water to binder ratios—0.65 and 0.48—were utilised by the authors. According to the findings of the test for the migration of chloride ions, 65-M0-28 had a coefficient that was 1.1% lower than 65-M5-28, while 65-M0-360, which had a longer curing time, had a coefficient that was 20% higher than 65-M5-360. MgO performed similarly in concrete with w/b = 0.48 as well.

2. Materials and Methods

2.1. Materials

Materials utilised for this experiment were tap water, MgO, fly ash, cement CEM I 42.5R, fine and coarse aggregates, and cement. In this experimental campaign, no additives were employed. Portugal's Secil (Lisbon) produced Portland cement CEM I 42.5R. Two types of natural aggregates were used: siliceous sands (0/2 and 0/4), and coarse aggregates (with commercial grading according to the designations 2/6, 6/12, and 12/20 of EN 12620 [34]).

EDP-Gesto da Produço de Energia, S.A. provided a class F fly ash (with 58% SiO2 and 24% Al2O3) to the Sines Power Plant in Portugal. The purities of the two varieties of MgO utilised were 85.0% for the Spanish variety and 98.8% for the Australian variety. MgO-S has 4.9 m2/g of specific surface area while MgO-A had 51.2 m2/g. For the Spanish and Australian MgOs, the reactivity was 3544 seconds and 14 seconds, respectively. Additionally, Liska et al. [12] showed that MgO's reactivity tends to rise as the specific surface area rises. Secil also provided the fly ash needed to make concrete. The particle sizes of the various binders are listed in Table 1.

Table 1 clearly demonstrates that MgO-A particles are smaller in size than MgO-S particles.

Table 1. Particle size of the different binders.

Material	<3 μm (%)	Between 3 and 32 μm (%)	>32 μm (%)
OPC	25.9	56.2	17.9
FA	21.3	55.9	22.8
MgO-S	12.1	15.3	72.6
MgO-A	40.1	56.0	3.9

2.2. Composition of the Mixes

The reference concrete's composition may be found in Table 2. Only the RM mix's composition is given because the others are identical.

The composition of each mix was established using a method described by Nepomuceno et al. [35]. A consistency class S2 and a strength class C30/37 were established to describe the reference concrete. To keep all of the mixtures within the S2 consistency class, various water/binder ratios were employed. The amount of each binder, according to specified and described percentages, is the sole difference in the other mixtures' make-up. 21 different concrete mixtures were created in all, including reference concrete (RC), mixtures with replacement ratios of 5%, 10%, and 20% for MgO-A and MgO-S, respectively, and mixtures with additions of 15% and 30% for fly ash, either with or without MgO. Each mixture is designated as Cx/y:FA/MgO-A or Cx/y:FA/MgO-S, depending on how much FA and how much Australian or Spanish MgO it contains.

Table 2. Composition of the reference concrete (RC).

Binder		0.098
Fine aggregates	0–0.063	0.001
	0.063–0.125	0.004
	0.125–0.25	0.030
	0.25–0.5	0.079

	0.5–1	0.097
	1–2	0.085
Coarse aggregates	2–4	0.036
	4–5.6	0.012
	5.6–8	0.050
	8–11.2	0.072
	11.2–16	0.153
	16–22.4	0.092
Water		0.174
Voids		0.017
Total		1.000

2.3. Tests

The experimental campaign would be divided into three parts. First, evaluations of the various components of concrete were conducted. Then, the fresh and hardened states of the concrete mixtures were examined. The aforementioned tests were carried out in order to categorise the various blends according to their durability. According to LNEC E-393 (1993) [36], the water absorption by capillarity was assessed in 3 specimens at 28 and 91 days. Based on LNEC E-394 (1993) [37], water absorption by immersion was assessed after 28 days in 3 specimens. According to NT BUILD 492 (1999-11) [38], the diffusion coefficient test for chloride penetration resistance was carried out at 28 and 91 days in 3 specimens for each age. Finally, based on LNEC E391 (1993) [39], the carbonation depth was measured at 7, 28, 56, and 91 days of maturity. For either 28 or 91 days, all specimens were kept in a humid room.

3. Results and Discussion

3.1. Consistency

The consistency of the mixes tended to decline as the incorporation ratio of reactive MgO increased. As reactive MgO increased, it became essential to increase the water/binder ratio in the mixes to maintain the desired consistency, as seen in Figure 1.

According to Figure 2, all mixtures fall into the S2 consistency (50-100 mm) category. When comparing the two types of MgO (from Spain and Australia), more water was needed in the mixture when using the MgO from Australia. The MgO-A particles' increased fineness and specific surface area are to blame for this, as the more surface area they have, the more water is needed to be absorbed by their surface.

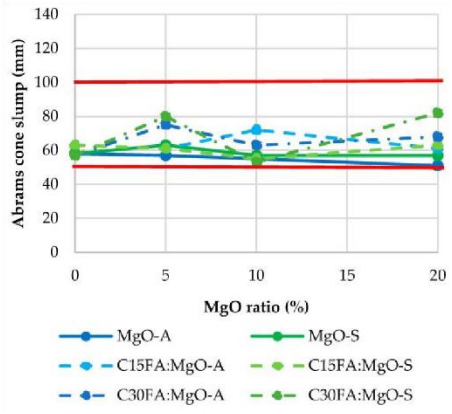
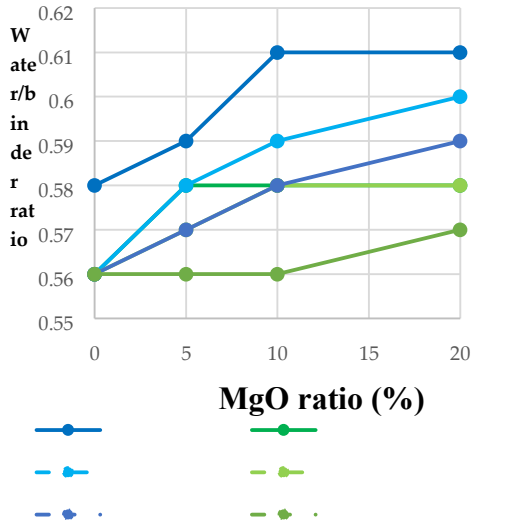


Figure 1. Abrams cone slump.



3.2. Capillary Water Absorption

First, Figures 3 and 4 demonstrate, respectively, the findings of water absorption via capillarity at 28 and 91 days for concrete with the addition of MgO. The amount of water absorbed by capillarity tends to significantly increase when MgO is present. In fact, the water absorption increases with the amount of MgO absorbed. When MgO-A was employed, it was feasible to have superior outcomes, particularly after 91 days. This effect could be caused by the MgO-S particles' higher porosity and reduced specific surface area.

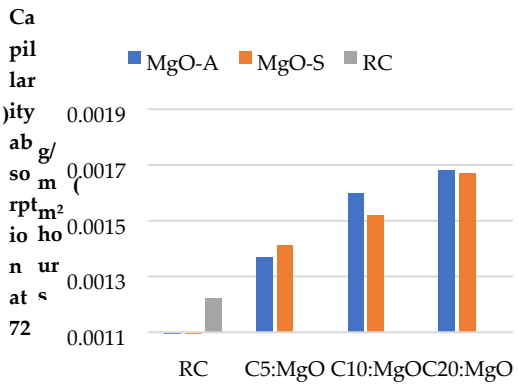


Figure 3. Water absorption by capillarity at 72 h versus MgO content, at 28 days.

It is possible to evaluate the water absorption through capillarity in concrete with MgO and FA at 28 and 91 days by analysing Figures 5 and 6. By including MgO and FA in the composition of concrete, it has been determined that the capillary absorption capacity tends to rise together with the amount of these two minerals. Once more, tests done at 28 days reveal greater values for this ability than those done at 91 days. The mixture C15/5:FA/MgO had the best results, increasing by roughly 4% in comparison to RC at both 28 and 91 days. Once more, MgO-A seems to produce superior outcomes versus its Spanish cousin. When these two materials are used together, as shown in Table 3, the outcomes are consistently better than those predicted theoretically (i.e., the total of the effects of each element's separate location). When the RC:15FA mix exhibits comparable values after 91 days after MgO addition, this is rather simple to see. The combined use of MgO and FA in the creation of concrete therefore looks intriguing in terms of this feature.

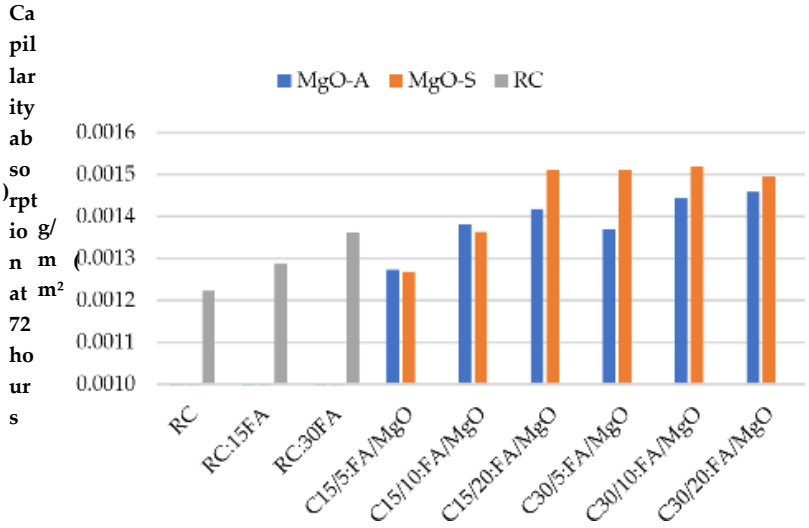


Figure 5. Capillarity absorption at 72 h in mixes with MgO and FA at 28 days.

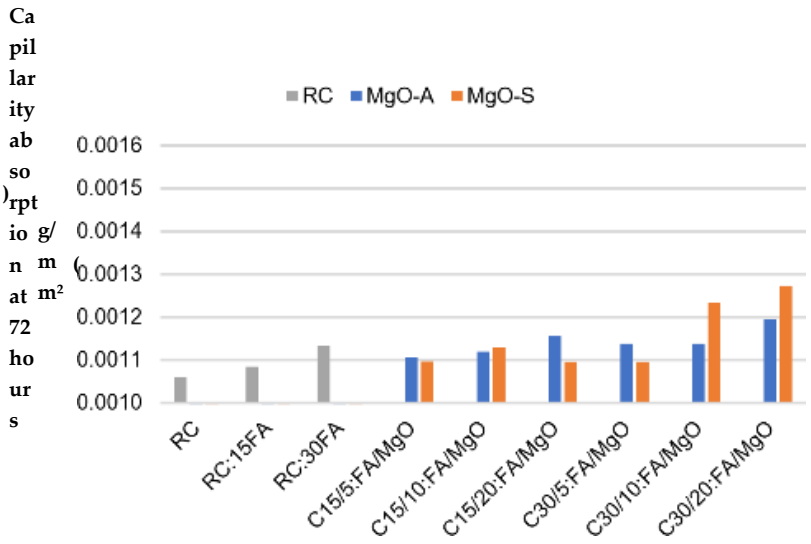
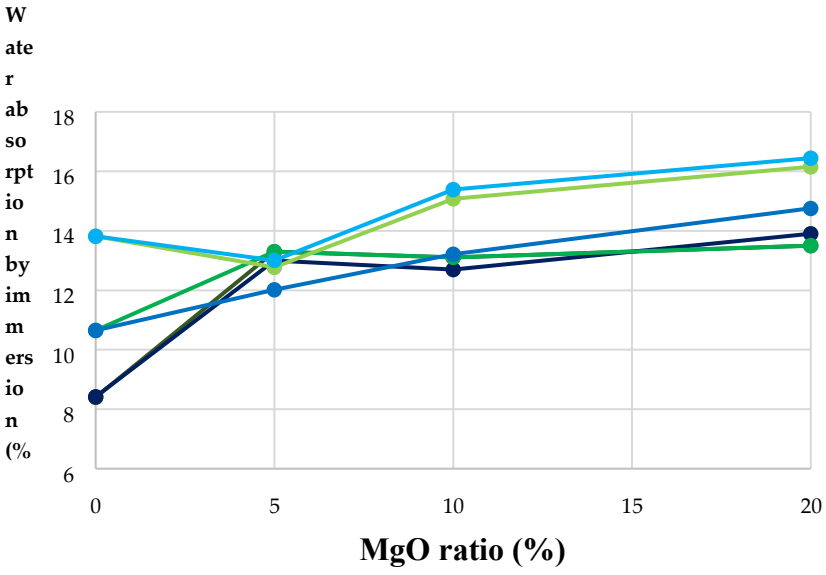


Figure 6. Capillarity absorption at 72 h in mixes with MgO and FA at 91 days.

3.3. Water Absorption by Immersion

Figure 7 demonstrates that when the incorporation ratio of MgO and FA rises, the water absorption by immersion at 28 days tends to rise. For the usage of 5% and 20% MgO-A, respectively, the variance fluctuates between increases of 54% and 65% with regard to RC when using only MgO-A. For the Spanish version, comparable values were found. The C30:FA/MgO mixtures produced the poorest results, as was to be expected, with an absorption of roughly 16% for both MgOs, about tripling the RC value. It should be emphasised, nonetheless, that the combination of these substances (MgO and FA) exhibits an improvement in comparison to the predicted theoretical value. This may be demonstrated by investigating mixtures like C15/10:FA/MgO-A. In comparison to RC, the RC15:FA mixture absorbs water with a 26.5% greater efficiency. The C10:MgO-A mixture exhibits a 51% rise. The absorption capacity would thus be anticipated to rise by 77.5% as compared to RC with combined usage.



MgO-SMgO-A

C15:FA/MgO-SC15:FA/MgO-A

C30:FA/MgO-SC30:FA/MgO-A

Figure 7. Water absorption by immersion at 28 days.

3.4 Carbonation

The carbonation depth of concrete mixes that were cured in a chamber with 5% CO2, 60% RH, and a temperature of 23 C is shown in Figures 8–10 at 7, 28, 56, and 91 days. It is instantly apparent that the carbonation depth rises with the addition of MgO and FA. In fact, the carbonation tends to display larger values as the percentage of these ingredients in the mixtures increases. Several factors led to the expectation of this phenomena. First, the mixes with MgO and/or FA have more porous matrix due to the rise in the water/binder ratio.

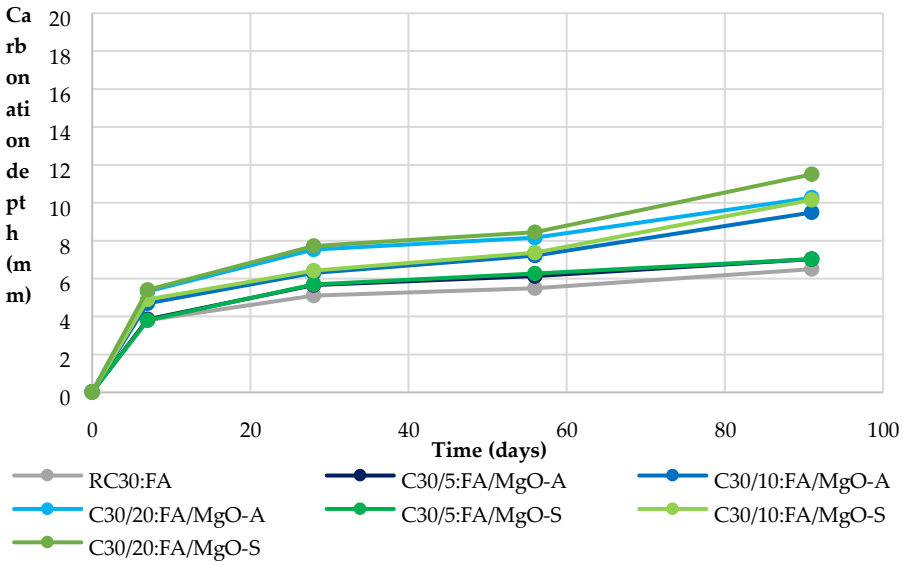


Figure 10. Carbonation depth in mixes with MgO and 30% FA.

The partial substitution of Portland cement, on the other hand, results in lesser creation of C-S-H and Ca(OH)2, and their interaction would slow the rate of carbonation. Additionally, according to Gonçalves et al. [19], the phenolphthalein test results suggest an enhanced rate of carbonation due to the decreased amount of Ca(OH)2, which has a pH level of 12.5, and an increased amount of Mg(OH)2, which has a pH level of 10.5. This, together with the fact that the microstructure is more porous than in RC, will be pretty cogent explanations.

Results from the Spanish MgO are less favourable than those from the Australian MgO.

3.5. Resistance to Chloride Penetration

Figures 11–13 summarize the chloride penetrability test results at 28 and 91 days. As expected, it is evident that with the incorporation of MgO and FA, the chloride ion migration coefficient increases.

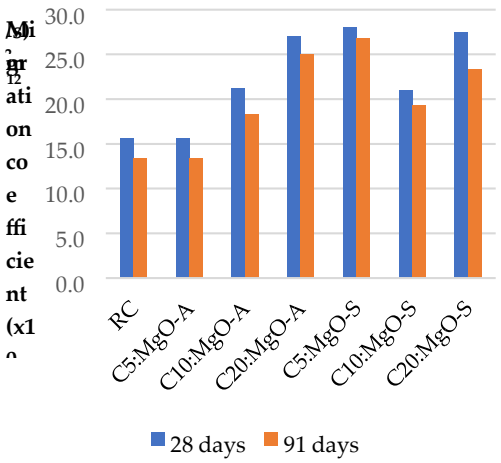


Figure 11. Chloride ion migration coefficient in mixes with MgO.

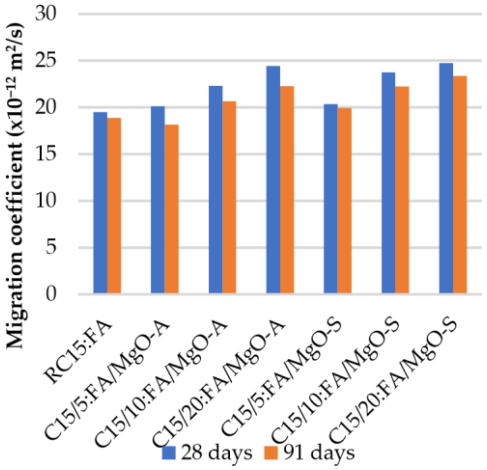


Figure 12. Chloride ion migration coefficient in mixes with MgO and 15% FA.

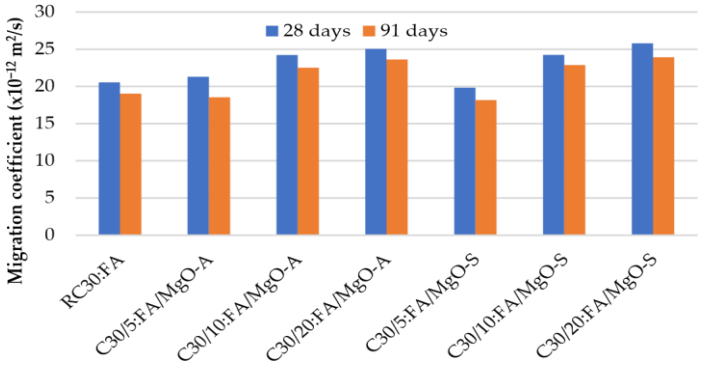


Figure 13. Chloride ion migration coefficient in mixes with MgO and 30% FA.

The use of 20% MgO produced the poorest outcomes, with a 100% increase in the chloride ion penetration coefficient in comparison to RC. Similar to the preceding attributes, Table 5 demonstrates that the theoretical value anticipated for the mixture of MgO and FA is significantly greater than the value discovered in the lab. Therefore, adding MgO and FA to concrete at the same time has advantageous effects on these characteristics as well. The coefficients at 91 days have lower values than those at 28 days, as would be predicted. This indicates that the barrier to chloride penetration gradually gets a little better. Numerous studies have compared the capillary absorption of water with the penetration of chloride ions. Ferreira [40] came to the conclusion that there is a linear relationship between the chloride ion diffusion coefficient and capillary water absorption. According to Figure 14, which illustrates a decent linear connection between both qualities in the concrete mixes included in this experiment, the coefficient of determination at 28 days was 0.74.

3.6. Comparative Analysis of Concrete Compressive Strength and Durability

To determine whether there is a correlation between the various durability features, it is crucial to correlate the compressive strength with those parameters. A compressive strength of 44.2 MPa was attained for the reference concrete at 28 days, and a compressive strength of 48.3 MPa was attained at 91 days. Table 6 shows how the ternary mixes' (OPC, MgO, and FA) stated attributes differ from the reference concrete.

Table 6. Mechanical and durability behavior of the different mixes.

Mix	Variation Relative to RC (%)					
	Compressive Strength		Water Absorption by Capillarity Immersion	Water Absorptio by	Carbonation Depth	Chloride Penetration
	28 Days	91 Days	91 Days	28 Days	91 Days	91 Days
C15/5:FA/MgO-A	−26.9	−15.5	+4.40	+42.7	+39.6	+35.4
C15/5:FA/MgO-S	−23.1	−13.7	+3.43	+39.5	+46.0	+48.6
C15/10:FA/MgO-A	−29.3	−15.5	+5.65	+57.0	+75.5	+53.9
C15/10:FA/MgO-S	−30.5	−17.3	+6.54	+65.4	+72.7	+65.7
C15/20:FA/MgO-A	−41.1	−34.5	+9.03	+75.3	+90.1	+66.0
C15/20:FA/MgO-S	−44.8	−36.8	+3.38	+82.1	+94.9	+74.1
C30/5:FA/MgO-A	−34.6	−15.0	+7.30	+54.4	+5.4	+38.1
C30/5:FA/MgO-S	−34.1	−18.9	+3.34	+51.7	+5.4	+35.4
C30/10:FA/MgO-A	−46.9	−29.1	+12.77	+82.8	+42.4	+67.7
C30/10:FA/MgO-S	−42.6	−26.2	+16.41	+79.9	+52.4	+70.5
C30/20:FA/MgO-A	−58.2	−39.5	+17.13	+95.3	+54.0	+76.0
C30/20:FA/MgO-S	−59.1	−38.5	+20.11	+91.9	+72.5	+78.2

In terms of compressive strength, it is evident that the strength capacity of concrete decreases with the partial inclusion of MgO and FA. In fact, the observed loss in this capability relative to the reference concrete increased with the amount of MgO and FA added. The compressive strength of ternary mixtures fell between 23% and 60% at 28 days compared to RC.

However, by 91 days of age, this decline was just 13% to 40%, demonstrating that these concrete mixes behaved better as the curing period increased.

It is obvious that the degradation of concrete's mechanical strength is followed by lower durability outcomes. All durability parameters evaluated perform poorly when MgO and FA are present in the same concrete mix. A poorer behaviour of ternary mixtures is also shown when the amount of these elements rises. Concrete containing MgO and FA exhibits similar behaviour in terms of mechanical and durability qualities. This phenomena is demonstrated by demonstrating that concrete's compressive strength degrades when MgO and FA levels rise in the cement matrix. The durability result was also similar.

4. Conclusions

The purpose of this research was to examine the durability effects of concrete that contained some MgO and fly ash. When fly ash and/or 5%, 10%, and 20% MgO were used in lieu of Portland cement, it was able to analyse the associated variances. When one or both of these components were present in comparison to the reference concrete, outcomes were nearly universally poorer.

Additionally, it was discovered that Spanish MgO often performs poorer than its Australian equivalent. This was caused by its smaller specific surface area, which also led to a smaller reactivity. These properties make the cement paste more porous. It is well knowledge that concrete's durability behaviour is greatly influenced by the cement paste's porosity.

It has been determined by integrating MgO and FA into the composition of concrete that as the amount of these two components increases, so does the capillary absorption capacity. At 28 days of curing age, there was an increase in all mixes created for mixes that simultaneously included MgO and FA, ranging from 3.7% (C15/5:FA/MgO-S) to 24.3% (C30/10:FA/MgO-S).

In the water absorption by immersion capacity at 28 days, a similar pattern of behaviour was seen. The findings were worse when the two materials were mixed. Individually, merely 15% FA results in an improvement in water absorption capacity of 26.5%. Comparing concrete containing 30% FA and 20% MgO-A to normal concrete, the findings are remarkably comparable, with the increase in this characteristic being 64% and 65%, respectively. The mixture C15/5:FA/MgO-S produced the highest results when MgO and FA were used together, increasing by 39.5% compared to RC.

Similar findings were found after observing the carbonation depth measurements. For C20:MgO-S, the worst outcome was seen, with a 160% rise in carbonation depth after 91 days. But as compared to RC, using FA led to an improvement.

The mixture RC30:FA yielded the lowest carbonation depth measurement.

The chloride ion migration coefficient rises as predicted with the addition of MgO and FA. The use of 20% MgO produced the poorest outcomes, with a 100% increase in the chloride ion penetration coefficient in comparison to RC. As previously mentioned, the penetration of chloride ions increases with increasing MgO and FA content in the cement matrix of concrete

for all mixes, with the best value being achieved when using 30% FA and 5% MgO, leading to an increase of 35.4% in this property compared to RC.

Similar tendencies to those seen in the durability parameters were discovered by analysing the compressive strength at 28 and 91 days. The mechanical capacity is reduced as a result of OPC's partial replacement. A lower durability behaviour of the non-conventional concrete goes hand in hand with this drop. Thus, it may be deduced that MgO and FA have a detrimental effect on the mechanical and durability properties of concrete.

One of the most crucial findings was that the negative impacts were not entirely overlapping in any of these attributes. When FA and MgO are mixed, the findings show an improvement in comparison to the predicted theoretical outcome. The total of each material's separate impacts equals the theoretical value. It was shown that the results achieved in ternary mixtures were superior to the anticipated theoretical outcomes for all of the analysed parameters. Particularly, the resistance to chloride ion penetration and carbonation depth showed improved.

In conclusion, it is evident that using MgO and FA together produces better outcomes than would be predicted based just on theory. The OPC replacement ratio, however, is greater than the observed variance, with the exception of water absorption through capillarity. The simultaneous use of these materials appears to be more effective, but additional research is required to determine the optimal ratio of their integration that could produce superior outcomes. In this study, it looks intriguing to include 5% MgO and 15% FA into concrete. On the other hand, it seems excessive to replace 50% of OPC.

The use of fly ash and reactive magnesium oxide as partial substitutes for Portland cement in the making of concrete has several practical advantages. First and foremost, these materials are affordable and easily accessible, which makes them a desirable choice for architects and engineers looking to increase the resilience and sustainability of their designs. Active magnesium oxide and fly ash may also make concrete more workable, making it simpler to pour, mould, and shape into the appropriate form. This can be especially useful for building projects when complicated or sophisticated designs are necessary, such when creating high-rise structures, bridges, or other infrastructure. Reactive magnesium oxide and fly ash can be used to extend the life and increase the security of concrete buildings from a maintenance standpoint. Buildings should survive longer and require fewer maintenance and repairs if concrete's resistance to cracking is improved.

Fly ash and reactive magnesium oxide work well as partial substitutes for Portland cement in the making of concrete. To fully explore and maximise the possibilities of these alternate materials, however, more study is required.

Investigating the effectiveness of concrete mixes with various concentrations of reactive magnesium oxide and fly ash is one area that needs more study. This would make it easier to determine the best combination for obtaining the highest levels of performance and sustainability while still being cost-effective. Additionally, research on the long-term resilience of concrete buildings made with reactive magnesium oxide and fly ash is necessary. This would include studying the effectiveness of these structures over a long length of time under various environmental conditions. The maintenance needs of concrete constructions

using various alternative materials might be determined with the use of this knowledge. Studying the impacts of employing reactive magnesium oxide and fly ash in combination with other environmentally friendly building materials, including recycled aggregates, in order to further lessen the environmental impact of concrete production, is another topic that needs more investigation. These study areas will be essential to maximising the performance, sustainability, and cost-effectiveness of these materials in concrete buildings for expanding cities and communities.

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