



# Article Performance of Pozzolan-Based Reactive Magnesia Cement Mixes against Sulphate Attack

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Abstract: Reactive magnesia cement (RMC) has gained interest due to its lower production temperatures when compared to Portland cement. In this study, the performance of pozzolan-based RMC concrete samples against sulphate attack was examined. Cube samples, after being removed from their moulds, were stored in a CO<sub>2</sub>-rich environment to gain compressive strength. Information obtained from XRD showed the formation of Mg carbonates in different forms. The use of fly ash and slag in large volumes reduces the environmental impact of concrete, but the use of these components have been found to greatly affect the formation of Mg carbonates in RMC mixes. This is mainly due to their filler effects. The coexistence of Ca- and Mg-based products was found in the slag-RMC mixes. The concrete samples based on RMC underwent mass and strength losses when stored in a MgSO<sub>4</sub> solution for up to 12 weeks. The removal of Mg from the microstructure of these samples was confirmed using SEM analysis. The use of the most widely used pozzolans at 50% by weight of the binder greatly affected the carbonation mechanism of the RMC mixes. This finding suggests that they should be limited in the design of Mg-based products that harden under CO<sub>2</sub>-rich conditions.

Keywords: reactive magnesia cement; fly ash; slag; carbonation; sulphate attack; microstructure



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# 1. Introduction

The production of Portland cement accounts for 5-10% of global anthropogenic CO<sub>2</sub> emissions, with it being manufactured at a calcination temperature of approximately 1450 °C [1]. In turn, reactive magnesia cement (RMC) is made in a temperature range of 700–1000 °C [2]. Cement hydrates gain compressive strength by being cured in water [3], whereas Mg-based products acquire strength by being stored in a CO<sub>2</sub>-rich environment [4]. RMC is a potential alternative to cement, which is the second most used material after water [5]. Mg-based products can significantly isolate  $CO_2$ , and their wide application in construction can reduce their carbon footprint. Brucite (i.e.,  $Mg(OH)_2$ ) forms as a result of mixing RMC with water, and it rapidly carbonates in a CO<sub>2</sub>-rich environment, in turn resulting in the production of hydrated magnesium carbonate (HMC). Dypingite  $(4MgCO_3 \cdot Mg(OH)_2 \cdot 5H_2O)$ , hydromagnesite  $(4MgCO_3 \cdot Mg(OH)_2 \cdot 4H_2O)$ , artinite  $(MgCO_3 \cdot Mg(OH)_2 \cdot 3H_2O)$ , and nesquehonite  $(MgCO_3 \cdot 3H_2O)$  are different forms of HMC and contribute to the development of compressive strength in RMC-based mixes [6]. They have round, prismatic, and rosette morphologies [7]. RMC particles are not very soluble in water, but they still turn into a strong binder during the formation of HMCs [8]. The carbonation of brucite is much slower in an ambient environment, and it should therefore be cured in an accelerated carbonation regime. This carbonation mechanism is also dependent on other factors, such as temperature, relative humidity, and CO<sub>2</sub> concentrations [9].

Pozzolanic materials are widely used for the modification of concrete properties. Fly ash and slag are solid waste materials obtained from thermal power plants and steel manufacturers, respectively. Their use in large volumes, as a replacement for cement, significantly reduces environmental impacts and material costs. Both these fine materials cause a filling effect, and also aid in the formation of secondary products in concrete matrices due to their pozzolanic activity [10]. This chemical reaction allows blended cement mixes to attain a compressive strength greater than that of control mixes at later ages [11]. Fly ash particles have a spherical morphology, and their incorporation improves workability and long-term durability [12]. However, gains in strength at initial ages are very weak due to the much slower hydration kinetics caused by them. The use of lowcalcium fly ash (as a cement replacement) in large volumes reduces concrete degradation in aggressive aqueous environments [13], but such a concrete modification is not desirable under freeze-thaw conditions [14]. Slag is a by-product of the steel industry, and when used in concrete mixes, it has shown numerous performance benefits. Previous studies have shown that the use of slag as a replacement for cement (up to 55%) has resulted in an increase in compressive strength [15]. Slag-based concrete mixes with reduced permeability have improved chloride binding capacities, leading to the significant production of Friedel salts [16]. The formation of calcium aluminosilicate hydrate (C-A-S-H) and hydrotalcite in conjunction with calcium silicate hydrate gel (C-S-H) reduces the pore volume [17] and strengthens the cement matrix [18]. Magnesium silicate hydrate (M-S-H) and hydrotalcite form in RMC-based mixes modified with fly ash and slag. They transform into HMC and magnesium calcite in a  $CO_2$ -rich environment. This uptake of  $CO_2$  alters the morphology of stable carbonates and facilitates their agglomeration [19], in turn leading to the densification of the microstructure of the binder matrix [20]. The use of fly ash in carbonated RMC mixes facilitates carbonate agglomeration and improves morphology due to the formation of HMC and magnesium calcite (Mg-CaCO<sub>3</sub>) [21]. Taking into account the global warming potential (GWP), the addition of 30% of fly ash in concrete mixes has been shown to decrease the GWP to 22% [22]. Similarly, RMC mixes based on fly ash exposed to a higher concentration of CO<sub>2</sub> attain strength rapidly with much lower CO<sub>2</sub> emission [23]. Slag-RMC mixes exposed to high concentrations of CO<sub>2</sub> (~about 99%) for 56 days have an increased compressive strength due to the formation of calcite and magnesium calcite [24]. Pozzolanic reaction products form along uncarbonated zones because of slag in concrete mixes, resulting in a more densified microstructure. There have been quite a few studies concerning both the strength development and reaction products of carbonated RMC mixes containing fly ash and slag. However, there is very little information on the action of chloride and sulphate ions on carbonated RMC mixes.

Sulphate attack is one of the most common causes of concrete deterioration, and can develop in many types of structures both above and below the ground [25]. This degradation occurs due to the expansive growth of ettringite and/or thaumasite within a concrete surface, often leading to the formation of surface-parallel cracks infilled with sulphate reaction products [26]. Ettringite is formed due to chemical reactions between moisture-containing sulphates and cement components [27]. Thaumasite forms in situations where there is a source of both sulphate and carbonate species. The formation of thaumasite is greater when the temperature is below 15  $^{\circ}$ C [28]. The carbonate required for the formation of thaumasite can be externally derived from groundwater containing carbonate species [28]. This complex process eventually leads to the degradation of concrete properties that are highly interdependent [29]. The formation of expansive gypsum and ettringite leads to a loss of strength and stiffness, and further contributes to the degradation of concrete [30]. Slag activated with reactive MgO is highly resistant to sodium sulphate attack when compared to cement-activated slag. Ettringite and calcium aluminate hydrate are not found in slag-MgO mixes after sulphate attack [31]. The purpose of this study is to investigate the degradation of Mg-based products after an external sulphate attack. Concrete samples modified with pozzolanic materials were carbonated for up to 4 weeks and then soaked in MgSO<sub>4</sub> solution for up to 12 weeks. The losses in their mass and compressive strength were then recorded. The effects of fly ash and slag on RMC hydration and subsequent carbonation were also evaluated using isothermal calorimetry, X-ray diffraction (XRD), and thermogravimetric analysis (TGA). An SEM study was conducted on degraded concrete

surfaces in order to examine the removal of Mg from the matrices due to sulphate attack. These experimental results provide valuable information concerning the effects of pozzolan on the performance and degradation of Mg-based products in extreme environments.

## 2. Materials and Methods

# 2.1. Sample Preparation

The RMC (i.e., calcined magnesite 92/200) was obtained from Richard Baker Harrison, while the siliceous fly ash and slag were obtained from Engro Corporation. These raw materials were analysed using a Cilas model particle size analyser and a Rigaku model X-ray fluorescence (XRF) instrument in order to determine their average particle size and chemical composition. The average size of their particles is within the range of 14–17  $\mu$ m, which was interpreted from the test results shown in Figure 1. A semi-automatic pelletiser was used to compact a powder sample in a circular metal disc, which was then analysed using XRF to obtain the data presented in Table 1. In this study, fly ash of anthracite origin was used. RMC is mainly composed of MgO, while slag, which is rich in CaO and SiO<sub>2</sub>, tends to form Ca-based products in RMC mixes. The samples were heated to 1000 °C in order to determine the loss of ignition (LOI), which was higher in the case of the RMC and slag than in the case of fly ash. Figure 2 shows the XRD results of these raw materials. The powder samples were ground to a size of less than 45  $\mu$ m using a standard sieve and then scanned using a Bruker D8 model XRD with a source of Cu K $\alpha$ . The operating current was 40 mA, and the voltage was 40 kV. Mullite and quartz minerals were found in the fly ash, periclase in the RMC, and traces of calcite and quartz in the slag. Granite aggregate of a maximum size of 9.5 mm was used under saturated dry surface conditions during the preparation of the samples. The properties of the aggregate were evaluated according to EN 12620 [32] guidelines. The average specific gravity and water absorption of the aggregates were determined to be 2.6 and 0.4% by weight, respectively. The addition of crushed sand affects the carbonation mechanism of Mg-based products and therefore was not considered when designing the concrete samples. The RMC-based concrete mixes were made with an aggregate-to-binder ratio of 1.5, with their details being listed in Table 2. The raw materials were mixed in a Hobart mixer with a capacity of 60 L for four minutes. The fresh mix was sticky but did not flow. It was put into an acrylic mould (size: 50 mm  $\times$  50 mm) in two equal layers, which were consolidated using a vibrating table. The top surface was smooth-finished using a flat blade. The cube sample was demoulded after 72 h and stored in a concrete carbonation chamber for up to 4 weeks. During this period, the temperature inside the chamber was maintained at 25  $^{\circ}$ C, the concentration of CO<sub>2</sub> was 10%, and the relative humidity (RH) was 70%. The demoulding period of the concrete samples was decided based on several experimental trials because they contain pozzolanic materials, which lower the rate of strength development at initial ages. Figure 3 illustrates the sample mixing process and carbonation treatment.

Table	1.	XKF	results	ot	the raw	material	s.

Oxide Compounds	RMC (%)	Fly Ash (%)	Slag (%)
Calcium oxide, CaO	1.6	1.2	37.8
Silicon dioxide, SiO <sub>2</sub>	2	58.6	32.3
Aluminium oxide, $Al_2O_3$	-	30.4	16.6
Iron oxide, $Fe_2O_3$	0.6	4.7	0.8
Magnesium oxide, MgO	91.5	-	9.3
Potassium oxide, $K_2O$	-	1.5	-
Titanium dioxide, TiO <sub>2</sub>		2	-
Refractory oxide, $R_2O_3$	1	-	-
Loss on ignition, LOI	3.3	1.6	3.2



Figure 1. Particle size distribution of the raw materials.



Figure 2. XRD results of the raw materials used in the study.

Table 2. Details of the concrete mixes (in kg).

Mix	RMC (kg)	Fly Ash (kg)	Slag (kg)	Aggregate (kg)	Water (kg)
M1	1000	-	-	1500	400
M2	500	500	-	1500	400
M3	500	-	500	1500	400



Figure 3. Preparation of the RMC based concrete samples.

### 2.2. Isothermal Calorimetry

The heat flow due to the hydration of the fresh cement mixes was studied using an I-Cal 8000 isothermal calorimeter (Calmetrix, Boston, MA, USA), which is in accordance with ASTM recommendations [33]. This test was carried out in a controlled environment that was maintained at 25 °C and 65% RH. The fresh samples were loaded directly into the calorimeter's channels within a few seconds after mixing. Heat flow was recorded for a period of up to 72 h.

## 2.3. External Sulphate Attack

Laboratory grade MgSO<sub>4</sub> salt in anhydrous form was obtained from Sigma-Aldrich. A stock solution containing 5% MgSO<sub>4</sub> and distilled water was prepared in a laboratory environment and used to carry out this experiment according to the procedure suggested by Lee et al. [34]. Analytical grade  $H_2SO_4$  was slowly added until the pH of this solution mixture reached 6–8. The concrete samples after 4 weeks were stored in a plastic container with this solution. They were exposed to the MgSO<sub>4</sub> environment for up to 12 weeks. The external solution was replenished every week during the exposure period in order to accelerate the degradation of the concrete sample over time. Figure 4 shows the images of the degraded samples.



Figure 4. (A) The concrete samples stored in the MgSO<sub>4</sub> solution, and (B) the degraded samples.

#### 2.4. Compressive Strength Test

The concrete samples (size: 50 mm  $\times$  50 mm  $\times$  50 mm) were crushed on an Axiomtek model compression testing machine at a load rate of 50 kN/min in order to obtain the value of their compressive strength. The maximum load capacity of this machine is 3000 kN. The load rate was calculated according to ASTM standards [35]. The load at failure was divided by the cross-sectional area of a sample for calculating compressive strength. The average of four replicates was calculated.

#### 2.5. XRD and TGA

Small fragments were obtained from the concrete samples destroyed in the compression testing machine. The cement powders from these fragments were removed with care and ground to a size smaller than 45  $\mu$ m using a chisel, hammer, standard sieve, and pestle and mortar. These fine powders were analysed using an XRD instrument operating at a scan rate of 0.02° 2 $\theta$  per minute for a total scan range of 5–80°. They were also heated to 1000 °C at a rate of 10 °C/min in a Netzsch STA model TGA purged in a nitrogen environment. The identification of crystalline phases and further refinement using the Rietveld method, were performed using DIFFRAC EVA software (Release 5.0) with COD databases and TOPAS software. The remaining phases in the XRD information were amorphous content.

## 2.6. SEM

The concrete samples after the sulphate attack were cut using a diamond-tipped precision saw. The cut sections were dried in a vacuum environment for 48 h at 30 °C, epoxy-impregnated using a Buehler model vacuum impregnation machine, and left undisturbed for 8 h. The hardened epoxy polymer was then demoulded and polished with a MetaServ

250 model grinder polisher (Buehler, Uzwil, Switzerland) following the procedure outlined in an earlier study [36]. The polished sample was mounted on steel stubs using a carbon adhesive, and then analysed using a JEOL model SEM operated at a low voltage of 5 kV under the backscattered electron (BSE) imaging mode.

#### 3. Results and Discussion

# 3.1. Heat of Hydration

Figure 5 shows the results of the isothermal calorimetry test. The fresh RMC-based mixes exhibited an exothermic reaction when water was added to them. The partial replacement of RMC with pozzolans significantly reduced the development of heat in the fresh paste mixes. The plain RMC mix exhibited the maximum amount of heat about 6 h after mixing. The total heat released by the plain RMC mix after 72 h was calculated to be 465 Joules, but the addition of fly ash and slag reduced this heat to almost 58%. The first hydration peak was ignored because the paste ingredients were mixed outside the isothermal calorimeter, whereas the second peak was attributed to the hydration kinetics, and its intensity was reduced to almost half when the RMC was partially replaced with pozzolanic materials. The reactiveness of RMC particles with water is limited by the formation of a Mg(OH)<sub>2</sub> surface layer in unreacted MgO particles [37]. Brucite reacts with the SiO<sub>2</sub> compound of fly ash to form M-S-H [38]. The design of a slag-RMC mix, and its hydration process, influence the degree of formation of calcium silicate hydrate (C-S-H), ettringite, brucite, and hydrotalcite [39].



Figure 5. Isothermal calorimetry test results of the fresh cement pastes.

## 3.2. Strength Development

The fresh concrete mixes were found to be sticky and stiff due to the fact that superplasticisers were not used during the preparation of the samples. No significant changes in concrete workability were observed due to the presence of fly ash and slag particles that were added in large volumes. Consolidation was achieved using a vibrating table to reduce the formation of voids caused by entrapped air. The compressive strength of the RMC-based concrete samples presented in Figure 6 improved with an increased storage time in the carbonation chamber, regardless of the composition of the binder. The average compressive strength of the M1 mix was determined to be 27 MPa after 4 weeks. The strength development rate of the M1 sample between 7 and 28 days was calculated to be 61%, while those of the M2 and M3 samples were 85% and 51%, respectively. However, the partial replacement of RMC with fly ash reduced the strength of the concrete samples by up to 36%, but this loss of strength was marginal in the case of the slag-based mixes at the end of 4 weeks. The accelerated carbonation of RMC is well documented in the recent literature [40]. The carbonation of RMC can occur through the formation of MgCO<sub>3</sub> from hydrated Mg(OH)<sub>2</sub> (by CO<sub>2</sub> uptake) or by the addition of water (to form HMC, including nesquehonite, dypingite, and artinite). HMCs form a well-densified structure with good binding potential and therefore improve the compressive strength of RMC-based samples.  $CO_2$  pressure, temperature, and ionic strength control the reaction and composition of HMC. Wang et al. [41] found that the degree of carbonation and compressive strength of RMC-based mixes cured for a week at 10% CO<sub>2</sub> were comparable to the values of the same mixes cured for 24 h at 100% CO<sub>2</sub>. Although the CO<sub>2</sub> concentration determined the carbonation rate, 10% CO<sub>2</sub> gas was sufficient to accelerate carbonation [41]. The slow dissolution of MgO particles in water hinders the hydration of RMC, which in turn affects the subsequent carbonation process. Therefore, such an effect (associated with the low dissolution of CO<sub>2</sub>) can result in insufficient concentrations of magnesium and carbonate ions, leading to a low precipitation level of carbonates and, consequently, to a small improvement of compressive strength [42]. Pozzolans contribute to the long-term performance of concrete mixes due to their filling effect and secondary C-S-H reactions. Their additions decrease the development of compressive strength in the RMC matrices. This is because the fine pozzolanic materials, especially fly ash and slag, greatly fill the pores and defects in the beginning days, thus decreasing the diffusion of  $CO_2$  gas during the storage of such matrices in a carbonation chamber [21].



Figure 6. Compressive strength test results.

# 3.3. *Microstructural Assessment* 3.3.1. XRD

Figure 7 shows the XRD pattern of the concrete samples after 4 weeks. The main XRD peaks at the 13.5°, 16.6°, 18.5°, 21°, 26.8°, 32.4°, 42.8°, and 43.1° 20 positions correspond with nesquehonite, artinite, brucite, hydrotalcite, mullite, magnesite, periclase, and calcite, respectively. The reference codes of the Joint Committee on Powder Diffraction Standards for nesquehonite and brucite are JCP-00-020-0669 and JCP-00-007-0239. The formation of HMCs was noticed in all the samples, but they also contained periclase (i.e., unreacted MgO particles) in them. Quartz and mullite compounds were found in the M2 sample, suggesting the occurrence of unreacted fly ash particles. The X-ray intensities of brucite and magnesite were found to be relatively higher in the M1 sample than in the other samples. Continuing the storage of the M1 sample in the carbonation chamber may possibly transform the remaining brucite in them into carbonates. Table 3 shows the XRD quantification results. The M3 sample after 4 weeks had 10.3% of periclase, which is 3.8 times higher than in the M1 sample. The reaction of the RMC particles with potable water was even lower when slag was used instead of fly ash. Hydromagnesite (JCP-00-025-0513) is one of the HMCs that was not found in the slag-based mixes, but the presence of nesquehonite in them was significant. The calcite observed in the slag-RMC mix could have formed due to exposure to  $CO_2$ . Amorphous compounds were found in the M2 and M3 samples, which could be due to the coexistence of C-S-H and M-S-H in the slag-RMC mix and the occurrence of just M-S-H in the fly ash-RMC mix.



Figure 7. XRD results of the concrete samples after 4 weeks.

Table 3. XRD	quantification resul	lts in % b	y weight.
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Sample	M1	M2	M3
Brucite (Mg(OH) <sub>2</sub> )	38.7%	18.2%	10.3%
Periclase (MgO)	19.2%	20.7%	32.4%
Quartz (Si $O_2$ )	-	11.8%	3.1%
Magnesite (MgCO <sub>3</sub> )	22.4%	1.8%	4.2%
Hydromagnesite $(4MgCO_3 \cdot Mg(OH)_2 \cdot 4H_2O)$	14.7%	3.8%	-
Artinite (MgCO <sub>3</sub> ·Mg(OH) <sub>2</sub> ·3H <sub>2</sub> O)	1.2%	1.1%	-
Nesquehonite (MgCO <sub>3</sub> ·3H <sub>2</sub> O)	2.9%	2.4%	7.2%
Dypingite $(4MgCO_3 \cdot Mg(OH)_2 \cdot 5H_2O)$	1.2%	-	-
Mullite $(3A1_2O_3 \cdot 2SiO_2)$	-	29.4%	-
Hydrotalcite (Mg <sub>6</sub> Al <sub>2</sub> CO <sub>3</sub> (OH) <sub>16</sub> ·4H <sub>2</sub> O)	-	-	6.2%
Calcite (CaCO <sub>3</sub> )	-	-	13.9%
Amorphous phase	-	11%	22.1%

### 3.3.2. TGA

Figure 8 shows the TGA results of the concrete samples after 4 weeks. Both the weight loss and the first derivative of the sample weight with respect to temperature were obtained by heating the powdered sample to 1000 °C in an inert environment. Weight losses due to the evaporation of free water and the decomposition of magnesium and calcium carbonates in the pozzolan-containing RMC mixes were quantified according to the recommendations of Muthu et al. [43] and Scrivener et al. [44]. Table 4 presents the TGA quantification results. The total weight loss of the M1 sample was 44% and 34% higher than in the case of the M2 and M3 samples, indicating a lower formation of Mg-based products due to pozzolanic materials. The M3 sample had more calcite, which is due to the carbonation of the CaO compound present in the slag. This argument correlates well with the XRD and SEM results.



Figure 8. TGA results of the concrete samples after 4 weeks.

Table 4. TGA quantification results.

TGA Weight Losses	Temperature Range	M1	M2	M3
Evaporable water and HMC	50–170 °C	38.7%	18.2%	10.3%
Brucite and HMC	300–480 °C	19.2%	20.7%	32.4%
Magnesite and HMC	480-630 °C	-	11.8%	3.1%
Calcite	630–900 °C	22.4%	1.8%	4.2%
Total	50-1000 °C	14.7%	3.8%	-

## 3.3.3. SEM

The polished surfaces were analysed using SEM in order to obtain BSE images, which are illustrated in Figure 9. These images revealed the presence of different phases of Mg and unreacted particles, which possessed different greyscale levels. The M1 sample was found to be composed of hexagonal brucite plates, acicular nesquehonite needles, and hydromagnesite crystals (like rosette) after 4 weeks. In turn, the M2 and M3 samples had large amounts of fly ash and slag particles with spherical and angular morphologies. They did not reveal the extensive presence of different HMC phases, indicating the limited hydration and carbonation of the pozzolan-RMC matrices. The slag particles consist mainly of CaO and SiO<sub>2</sub>, and their reaction with water led to the formation of C-S-H in the M3 sample. This hydrate was found to have a dark grey tone surrounding the bright, unaltered slag particle.



Figure 9. SEM images of the concrete samples after 4 weeks.

# 3.4. Sample Degradation

There were no significant colour changes in the concrete samples after being stored in the MgSO<sub>4</sub> solution for up to 12 weeks, but their surfaces had traces of microcracks and defects. Figure 10 shows the losses in the mass and strength of the concrete samples due to the sulphate attack. These losses were found to be the highest in the slag-RMC mix. The average strength loss of the M3 sample at the end of the sulphate attack was around 6%, which is 1.4 times greater than that of the M2 sample. The use of fly ash and slag at large volumes reduced the environmental impacts of the RMC-based concrete mixes but did not contribute to improving the resistance of the material to degradation caused by sulphate attack. Thus, their use in Mg-based products should be limited to avoid the weak strength development at initial ages and for the products to be more durable when used in aggressive aqueous environments. The alumina in slag produces ettringite by reacting with the sulphate ions of the external solution, in turn leading to the expansion of concrete [45]. In contrast, siliceous fly ash improves concrete resistance to sulphate attack [46]. In this study, the addition of fly ash in large volumes refined the concrete microstructure, but affected the carbonation mechanism of the available Mg phases. Therefore, the resulting binder exhibited low strength and weak resistance to sulphate attack. The degraded surfaces of the concrete samples at the end of the sulphate attack were fine polished, and their microstructure was studied by collecting EDS information at multiple points. Figure 11 shows the results of these analyses performed on the degraded

concrete surfaces. Several points corresponding to the regions of brucite, magnesite, and periclase were observed in the concrete samples at the end of  $CO_2$  exposure. The points were in a region corresponding to low magnesium contents in the scatter plots, representing the leaching of magnesium ions from the concrete samples at the end of the sulphate attack.



Figure 10. Degradation properties of the concrete samples at the end of external sulphate attack.



Figure 11. EDS scatter plots revealing the sample degradation at the end of the sulphate attack.

# 4. Conclusions

The key findings of this experimental investigation are as follows:

- Brucite formed because of the reaction between RMC and water. The total heat released by the RMC mixes was reduced to almost half when they were modified with fly ash and slag at high volumes. This reduction in heat generation is of significant interest in various construction applications, as it offers benefits in terms of reducing thermal stresses, minimising the risk of cracking, and improving the overall durability of concrete structures.
- Brucite transformed into carbonates in a CO<sub>2</sub>-rich environment, but this carbonation
  of Mg(OH)<sub>2</sub> was affected by the presence of the fly ash and slag. The addition of
  these pozzolanic materials reduced the degree of carbonation of the RMC matrices
  due to the filler effect. XRD, TGA, and SEM studies confirmed the lower formation
  of magnesium carbonates in pozzolan-modified RMC mixes in comparison to plain
  RMC mixes. This finding is crucial in understanding how the inclusion of fly ash and
  slag alters carbonation kinetics in RMC-based systems.
- The compressive strength and mass of the concrete samples were reduced at the end of the external sulphate attack, but there was no significant colour change. The sulphate resistance of the slag-RMC mix was the lowest among all the concrete samples. The crucial finding from these experiments is the correlation between the amount of pozzolanic materials in Mg-based products and the ensuing consequences. An excessive presence of pozzolanic materials was observed to lead to a reduced degree of magnesium carbonation. Furthermore, the increased use of pozzolanic materials

in the RMC mix contributed to weaker resistance against the degrading effects of the sulphate-laden environment.

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