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Research Paper

Effect of Nano-MgO Additive on Compressive Strength of Concrete Fabricated by Different Processing Methods

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ABSTRACT

The effects of adding different nano-MgO dosages (0, 1, 2, 3, and 4 wt.% with respect to cement) on microstructural, compressive strength, and phase evaluation of concrete were investigated. Two different post-treatment conditions with water and CO_2 gas were used to study the processing method on the samples. The specimens were characterized via SEM and XRD analysis. The mechanical properties of the samples were also investigated. The results showed that compressive strength significantly improved after the addition of magnesium oxide nanoparticles. However, this improvement was more remarkable in the case of post-treatment with CO_2 compared to the samples fabricated with water. SEM results showed that the samples treated under CO_2 gas had irregular and needle-like morphology. The samples prepared by normal processing had $CaCO_3$ and SiO_2 phases, whereas the ones fabricated under CO_2 gas contained $CaCO_3$, SiO_2, and $Ca(OH)_2$. With the addition of nano-MgO, the density of concrete decreases in the samples post-treated with water, whereas it increases for the samples post-treatment with CO_2 gas. Adding 4 wt.% nano-MgO to concrete and further post-treatment with CO_2 for 45 days could increase the mechanical properties from ~ 23 MPa to ~ 55 MPa.

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1. Introduction

Nano dimension materials like nanoparticles, nanobelts, nanosheets, etc., have attracted much attention in the last 100 years [1]. In this dimension, the mechanical and physical properties of materials could be changed. This phenomenon has been extensively used in recent years in many industries like textile, chemical, plastic, cosmetics, and so on [2–4]. One of the essential subjects is to use of nanomaterials for improving the raw materials in the construction industry [5,6].

Portland cement may be a widely used building material in the world. Because of chemical, drying, and autogenous shrinkage caused by temperature stress, this material cracks quickly [7]. These cracks compromise building safety, diminish service life, and result in significant economic and societal losses. In addition, the formed cracks allow acidic chemicals to enter the concrete, causing carbonation, corrosion, and unwanted reactions. It could also destroy the steel in the reinforced concrete [8]. These events reduce the strengths of the structure [9]. Nanomaterials could be added to the concrete to improve the mechanical properties and inhibit these drawbacks. For example, some researchers added carbon nanotube [10,11] to concrete and showed that the nanomaterials ameliorate the properties of the structure. Promising results have also been reported with the addition of graphene [12–14]. Magnesium oxide (MgO) is a fascinating basic oxide ceramic with numerous applications [15]. This oxide ceramic can be used as an absorbent of toxic chemicals, refractories, catalyst support, optic instrument, etc. [16–20]. Volume expansion happens in this material when it reacts with water due to the formation of $Mg(OH)_2$. By adding MgO to concrete, this hydration and expansion could compensate for the contraction of concrete and may reduce the chance of crack formation [21,22].

This study aimed to add nano-MgO to concrete processed by two different methods (post-treated with water and carbon dioxide) to investigate its effects on the mechanical properties, phase evaluation, and microstructure. Although the MgO addition to concrete has been studied before, in the present work, the effect of nano-MgO was investigated based on the post-treatment processing of concrete which is a new approach.

Table 1. Chemical composition of Portland cement

Chemical Composition	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	K_2O	Na_2O	L.O.I
Weight percent	53.27	21.89	5.3	3.34	6.45	3.67	0.98	0.18	3.21

Table 2. The composition, code name, and applied curing condition of the samples

Curing Condition	Sample Code	Composition weight (g)					
		Cement	Stone Powder	Grit	Sand	Water	Nano-MgO
Water	0% MgO-N	333	167	625	708	120	0
	1% MgO-N	314.7	167	625	708	120	18.3
	2% MgO-N	296.4	167	625	708	120	36.6
	3% MgO-N	287	167	625	708	120	55
	4% MgO-N	260	167	625	708	120	73.32
CO_2	0% MgO-C	333	167	625	708	120	0
	1% MgO-C	314.7	167	625	708	120	18.3
	2% MgO-C	296.4	167	625	708	120	36.6
	3% MgO-C	287	167	625	708	120	55
	4% MgO-C	260	167	625	708	120	73.32

2. Experimental procedure

2.1. Materials and Methods

In the present study, Portland cement, Stone Powder, Grit, Sand, and water with the chemical composition shown in Table 1 were used. Nano-MgO was purchased from US-nano. Based on the compositions shown in Table 2, the raw materials were mixed. The MgO-mixed cement was made by adding different amounts of nano magnesium oxide to the Portland cement and other compounds mixture. The raw materials were mixed based on the ASTM C 305 [23]. The method includes the dispersion of nano-MgO in water by ultrasonic for 15 min in order to deagglomerate MgO nanoparticles. All the samples were produced with a water-to-cement ratio of 0.45 and produced in a laboratory mixer. For the construction of blocks, H_2O was added to the mixed samples for 3 min under stirring. The fresh pastes were cast in steel molds. The samples were covered with a polyethylene sheet to prevent water evaporation. After 24 h, the samples were demolded without slump. Then, the samples were subjected to CO_2 gas or immersed in water for 7, 30, and 45 days to investigate the effect of curing on the samples. The purity of CO_2 gas was 98%. Four samples were produced for each mixture and an average value of measurements with error bars was reported. The name of the samples was shown in Table 2.

2.2. Characterizations

The phase evaluation of the samples was analyzed by X-ray diffraction (Philips PW3040 diffractometer) with copper radiation. SEM images were taken with a VEGA/TESCAN Mira 3-XMU microscope. The compressive strength of the fabricated specimens was measured by uniaxial loading of 55 kN/min using a Toni Technik Baustoffprüfsysteme machine. The density (ρ) of samples was measured according to their size and weights based on equation 1.

$$\rho = \frac{Mass\ of\ sample\ after\ post-tratment}{Volume\ of\ sample\ after\ post-tratment} \quad \text{(Eq. 1)}$$

3. Results and discussion

Fig. 1 shows the XRD result and SEM image of the nano-MgO used for addition to the concrete. According to the XRD pattern of the sample (Fig. 1a), all of the peaks are related to the conventional cubic MgO reflections (JCPDS 45–0946). The (111), (200), (220), (311), and (222) MgO crystal planes correspond to the diffraction peaks at 36.6°, 42.5°, 61.8°, 74.0°, and 78.3°. SEM micrograph (Fig. 1b) shows that the powders have homogeneous spherical particles with an average particle size of about 30 nm. The nanopowders contain some aggregates and agglomerates. The high surface energy of the nanopowders causes the production of these agglomerates. As a result, nanoparticles tend to clump together in order to reduce their surface energy [24–27].

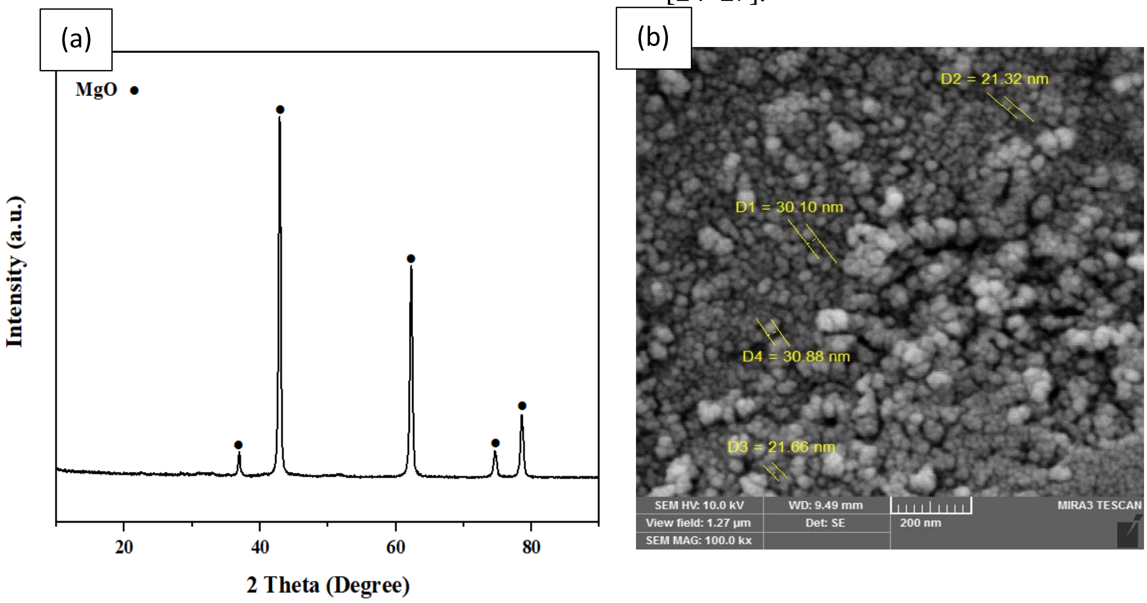

Fig. 1. (a) XRD pattern and (b) SEM image of the MgO.

Fig. 2 displays the XRD patterns of samples with different amounts of MgO post-treated with water and CO_2 gas for 45 days. As can be seen, in the sample post-treated with water, $CaCO_3$, SiO_2, and $Ca(OH)_2$ phases are observed. The formation of calcium hydroxide is due to a reaction between calcium oxide and water during post-treatment according to equation 2 [28].

$$CaO + H_2O \rightarrow Ca(OH)_2$$

ΔH=-104.2 kJ mol^{-1} (Eq. 2)

Due to variations in the specific volumes of $Ca(OH)_2$ (0.45 cm^3/g) and CaO (0.29 cm^3/g) [29], the sample expands during the reaction. The nano-MgO may also react with water and form magnesium hydroxide, which accompanies expansion. Due to the intrinsic contraction of concrete during reaction and drying, cracks form, which is harmful and reduces the mechanical properties. The expansion of formed hydrated phases after post-treatment compensates for the contraction of the concrete and reduces the chance of crack creation. The peaks related to magnesium oxide could not be detected in the samples, which may be due to the low amount of MgO in the samples. The samples with CO_2 post-treatment show $CaCO_3$ and SiO_2 components. Processing with carbon dioxide prevented the formation of hydrated phases. In this condition, the carbonate phases of calcium and magnesium may be formed.

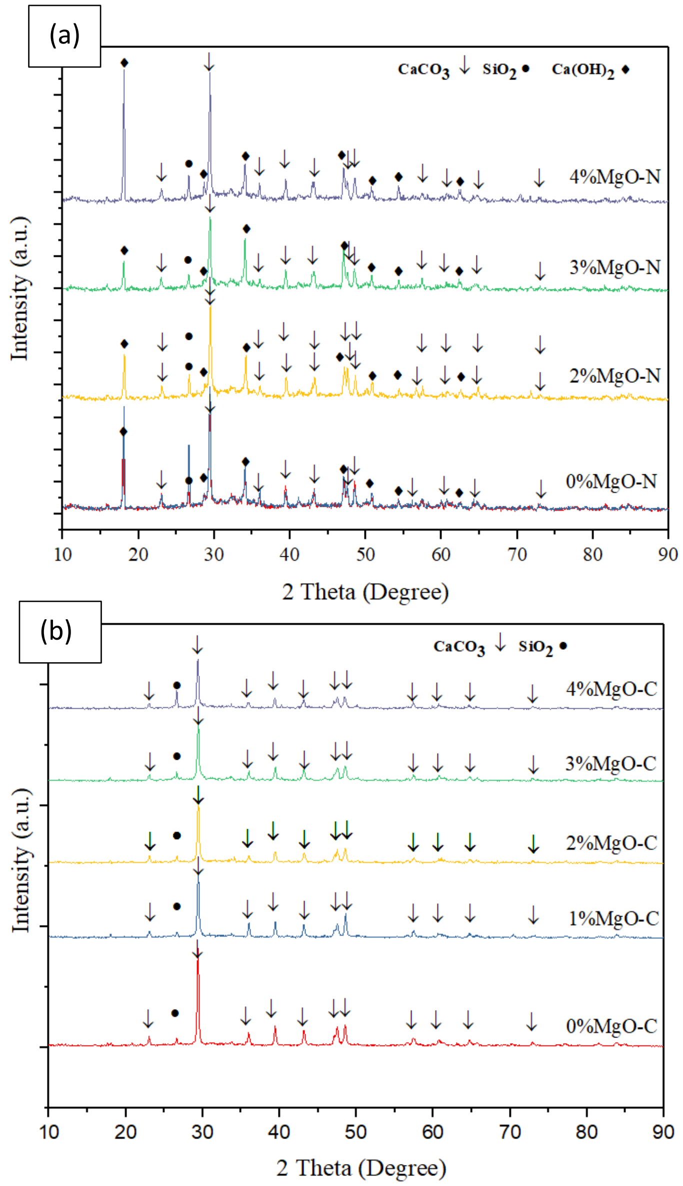

Fig. 2. XRD patterns of the fabricated samples with different nano MgO post-treated with (a) water and (b) CO_2.

The density of the samples with different amounts of MgO post-treated with water and CO_2 is shown in Fig. 3. As can be seen, nano-MgO has a different effect on the density of the samples. In the samples post-treated with water, by increasing MgO content, the density of concrete decreases. This reduction is due to the hydration of magnesium oxide (ρ=~3.58 g cm^{-3}) and the formation of $Mg(OH)_2$ (ρ=~2.34 g cm^{-3}). For the samples post-treated with CO_2, the density of samples increases by adding nano magnesium oxide. This increase may be accomplished by the creation of magnesium carbonate (ρ=~2.96 g cm^{-3}) from magnesium hydroxide (ρ=~2.34 g cm^{-3}) according to equation 3 [30].

$$Mg\,(OH)_2 + CO_2 \rightarrow MgCO_3 + H_2O$$

$\Delta H = -30.2$ kJ mol^{-1} (Eq. 3)

In addition to $MgCO_3$, the formation of the hydrated phase of magnesium carbonate has also been reported. In other words, the reaction between water and $MgCO_3$ can create nesquehonite ($MgCO_3.3H_2O$), dypingite ($Mg_5(CO_3)_4(OH)_2.5H_2O$), and artinite ($Mg_2(OH)_2CO_3.3H_2O$) [31,32]. Among these hydrated phases of magnesium carbonate, nesquehonite is more common in the CO_2 post-treatment [30]. It was reported that the formation of these hydrated phases could create a densified structure with high binding power, therefore improving the mechanical characteristics of the construction [33,34]. However, the formation of the prominent phase in the final products strongly depends on many factors such as temperature, CO_2 pressure, the humidity of CO_2 gas, etc. [35–38].

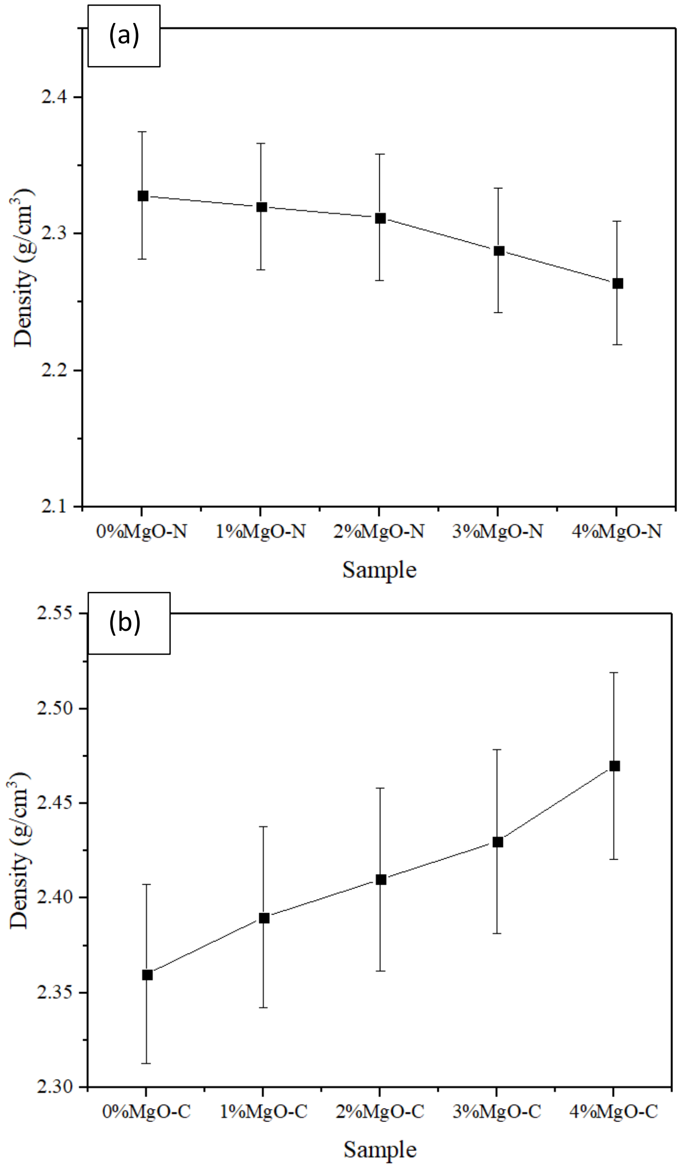

Fig. 3. The density of the samples with different amounts of MgO post-treated with (a) water and (b) CO_2.

Fig. 4 shows SEM micrographs of the samples with different amounts of MgO post-treated for 45 days with water and CO_2. As can be seen, the samples post-treated with water have particles with irregular and spherical morphologies, whereas the samples post-treated with CO_2 exhibit irregular and needle-like morphologies. The needle-like shape of particles in the carbon dioxide post-treated samples may be due to the formation of carbonate phases. There are some cracks and pores in the pure concrete, which could be attributed to the contraction of concrete during the drying. By increasing the nano magnesium oxide in the concreate, the number of cracks and pores is reduced. This reduction of the defects in the nano-MgO added samples is due to the volume changes during the formation of hydrated and carbonated phases during the post-treatment process. In other words, the expansion due to the formed phases reduces the contraction effect of the concrete [39,40].

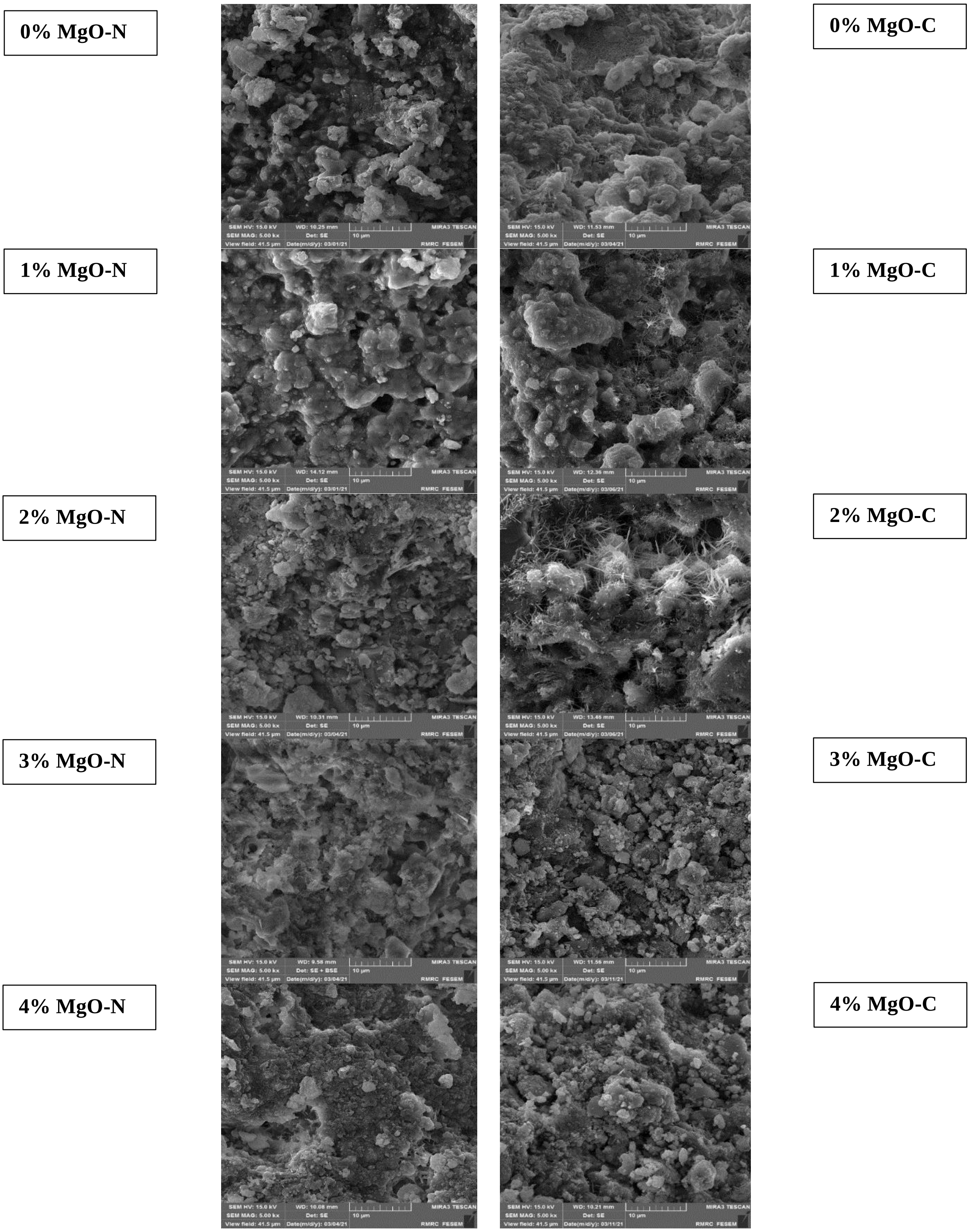

Fig. 4. SEM micrographs of the samples with different amounts of MgO post-treated with (a) water and (b) CO_2.

Fig. 5 represents the compressive strength of the samples with different amounts of MgO and post-treated with water and CO_2 on different days. It is clear that in all samples, with the increase of post-treatment days from 7 days to 45 days, the compressive strengths of the samples improve. This improvement could be attributed to the formation of hydrated and carbonated phases during post-treatment, which results in the reduction of the formed stress in the concrete. In addition, the addition of MgO leads to an improvement in the mechanical properties of the samples. The SEM results showed that adding MgO reduces the number of defects like cracks and pores, which may explain why nano-MgO ameliorates the compressive strength. In addition, it was reported that the improvement in the mechanical properties of samples by adding MgO could be due to its high activity and the seeding effect of these nanoparticles

[41]. It seems that post-treatment with CO_2 has a better effect on improving compressive strength. For instance, the 4% MgO-C sample reached a compressive strength of about 55 MPa, but the 4% MgO-N sample had a compressive strength of about 51 MPa after 45 days post-treatment. It is noteworthy that the uniform distribution of nano-size MgO in the concrete matrix is critical. It is because, during the hydration and carbonation of magnesium oxide, uniform stress would create in the microstructure, which results in the filling of pores and cracks. Therefore, it may cause better improvement in the mechanical properties of final products. It is noteworthy that high amounts of MgO or large-scale MgO may have an adverse effect on the mechanical properties of samples. For example, It was reported that high amounts of large-size magnesium oxide in the cement could cause extreme expansion, which results in the formation of cracks and reduction of mechanical properties. In the nanosized scale, the formation of these local stressed is reduced, which may improve these destructing expansion effects [42,43].

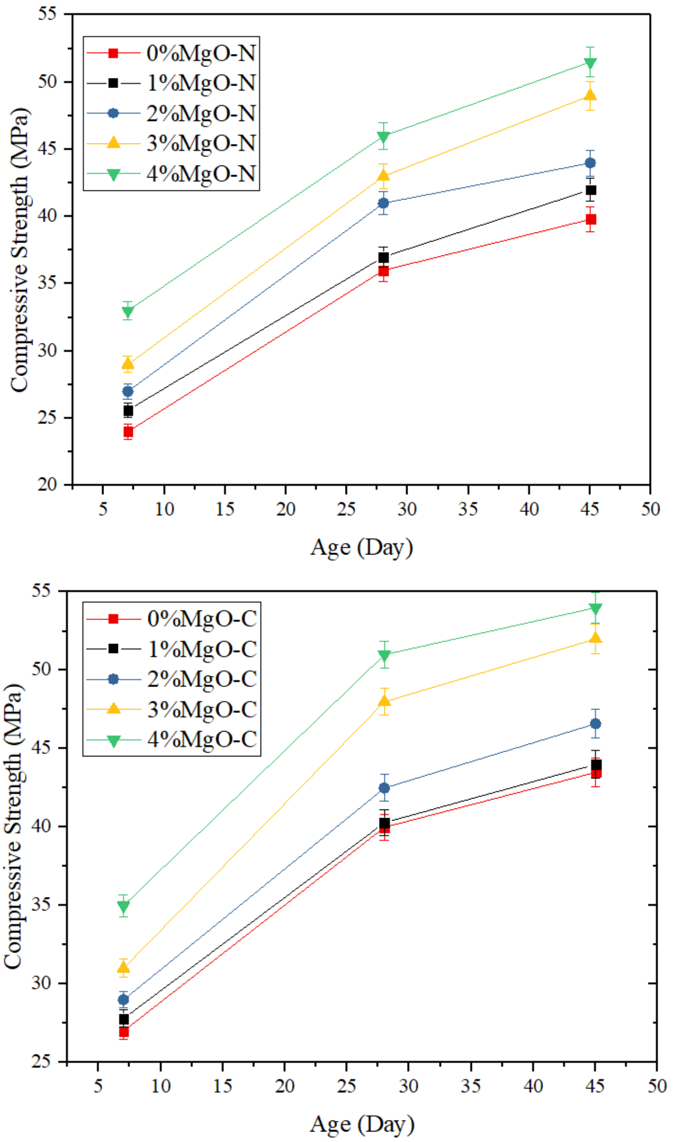

Fig. 5. Compressive strength of the samples with different amounts of MgO post-treated with (a) water and (b) CO_2.

4. Conclusions

The effect of two different post-treatment with water and CO_2 on the mechanical properties of the MgO-added concrete was investigated. The samples were studied via X-ray diffraction and Scanning electron microscopy. The XRD results showed that $CaCO_3$, SiO_2, and $Ca(OH)_2$ phases are formed in the post-treated samples with H_2O, whereas the hydrated phases are not observed in the post-treated specimens with CO_2. Compressive strength improved by adding nano-MgO and increasing the time of post-treatment. The samples post-treated in CO_2 had irregular and needle-like morphologies. The density of the samples post-treated with water decreases with adding nano-MgO, whereas the density of the ones post-treated with carbon dioxide increases by increasing magnesium oxide. Post-treatment of concrete with

CO_2 had a better effect on the ameliorating of mechanical properties than processing with water.

References

[1] N. Baig, I. Kammakakam, W. Falath, Nanomaterials: A review of synthesis methods, properties, recent progress, and challenges, Mater. Adv. 2 (2021) 1821–1871.

[2] G. Bhattacharya, S.J. Fishlock, J.A. McLaughlin, S.S. Roy, Metal-oxide nanomaterials recycled from E-waste and metal industries: A concise review of applications in energy storage, catalysis, and sensing, Int. J. Energy Res. 45 (2021) 8091–8102.

[3] M.A. Subhan, K.P. Choudhury, N. Neogi, Advances with Molecular Nanomaterials in Industrial Manufacturing Applications, Nanomanufacturing. 1 (2021) 75–97.

[4] C. Thongchom, N. Refahati, P. Roodgar Saffari, P. Roudgar Saffari, M.N. Niyaraki, S. Sirimontree, S. Keawsawasvong, An experimental study on the effect of nanomaterials and fibers on the mechanical properties of polymer composites, Buildings. 12 (2021) 7.

[5] M. Janczarek, Ł. Klapiszewski, P. Jędrzejczak, I. Klapiszewska, A. Ślosarczyk, T. Jesionowski, Progress of functionalized TiO_2-based nanomaterials in the construction industry: A comprehensive review, Chem. Eng. J. 430 (2022) 132062.

[6] A.A. Firoozi, M. Naji, M. Dithinde, A.A. Firoozi, A review: influence of potential nanomaterials for civil engineering projects, Iran. J. Sci. Technol. Trans. Civ. Eng. 45 (2021) 2057–2068.

[7] E. Enríquez, M. Torres-Carrasco, M.J. Cabrera, D. Muñoz, J.F. Fernández, Towards more sustainable building based on modified Portland cements through partial substitution by engineered feldspars, Constr. Build. Mater. 269 (2021) 121334.

[8] L. Wang, M. Jin, Y. Wu, Y. Zhou, S. Tang, Hydration, shrinkage, pore structure and fractal dimension of silica fume modified low heat Portland cement-based materials, Constr. Build. Mater. 272 (2021) 121952.

[9] Z. Li, B. Delsaute, T. Lu, A. Kostiuchenko, S. Staquet, G. Ye, A comparative study on the mechanical properties, autogenous shrinkage and cracking proneness of alkali-activated concrete and ordinary Portland cement concrete, Constr. Build. Mater. 292 (2021) 123418.

[10] Y. Liu, T. Shi, Y. Zhao, Y. Gu, Z. Zhao, J. Chen, B. Zheng, S. Shi, Autogenous shrinkage and crack resistance of carbon nanotubes reinforced cement-based materials, Int. J. Concr. Struct. Mater. 14 (2020) 1–10.

[11] T. Shi, Z. Li, J. Guo, H. Gong, C. Gu, Research progress on CNTs/CNFs-modified cement-based composites–a review, Constr. Build. Mater. 202 (2019) 290–307.

[12] Y. Zhao, Y. Liu, T. Shi, Y. Gu, B. Zheng, K. Zhang, J. Xu, Y. Fu, S. Shi, Study of mechanical properties and early-stage deformation properties of graphene-modified cement-based materials, Constr. Build. Mater. 257 (2020) 119498.

[13] C.J. Liu, X.C. Hunag, Y.-Y. Wu, X.W. Deng, Z.L. Zheng, B. Yang, Studies on mechanical properties and durability of steel fiber reinforced concrete incorporating graphene oxide, Cem. Concr. Compos. (2022) 104508.

[14] P. Reddy, D.R. Prasad, Investigation on the impact of graphene oxide on microstructure and mechanical behaviour of concrete, J. Build. Pathol. Rehabil. 7 (2022) 1–10.

[15] R. Pournajaf, S.A. Hassanzadeh-Tabrizi, R. Ebrahimi-Kahrizsangi, A. Alhaji, A.A. Nourbakhsh, Optimization of magnesia sintering parameters fabricated by spark plasma sintering method for infrared transparency, Mater. Res. Express. 8 (2021) 65002.

[16] S. Gandhi, P. Abiramipriya, N. Pooja, J.J.L. Jeyakumari, A.Y. Arasi, V. Dhanalakshmi, M.R.G. Nair, R. Anbarasan, Synthesis and characterizations of nano sized MgO and its nano composite with poly (vinyl alcohol), J. Non. Cryst. Solids. 357 (2011) 181–185.

[17] R. Pournajaf, S.A. Hassanzadeh-Tabrizi, R. Ebrahimi-Kahrizsangi, A. Alhaji, A.A. Nourbakhsh, Polycrystalline infrared-transparent MgO fabricated by spark plasma sintering, Ceram. Int. 45 (2019) 18943–18950.

[18] X. Xu, T. Zhu, Y. Li, Y. Dai, M. Nath, Y. Ye, N. Hu, Y. Li, X. Wang, Effect of particle grading on fracture behavior and thermal shock resistance of MgO-C refractories, J. Eur. Ceram. Soc. 42 (2022) 672–681.

[19] A.S. Farooqi, M. Yusuf, N.A.M. Zabidi, R. Saidur, M.U. Shahid, B.V. Ayodele, B. Abdullah, Hydrogen-rich syngas production from bi-reforming of greenhouse gases over zirconia modified Ni/MgO catalyst, Int. J. Energy Res. 46 (2022) 2529–2545.

[20] H.L. Senevirathna, P.V.T. Weerasinghe, X. Li, M.-Y. Tan, S.-S. Kim, P. Wu, Counter-Intuitive Magneto-Water-Wetting Effect to CO2 Adsorption at Room Temperature Using $MgO/Mg(OH)_2$ Nanocomposites, Materials (Basel). 15 (2022) 983.

[21] L. Wang, G. Li, X. Li, F. Guo, S. Tang, X. Lu, A. Hanif, Influence of reactivity and dosage of MgO expansive agent on shrinkage and crack resistance of face slab concrete, Cem. Concr. Compos. 126 (2022) 104333.

[22] L. Wang, X. Song, H. Yang, L. Wang, S. Tang, B. Wu, W. Mao, Pore structural and fractal analysis of the effects of MgO reactivity and dosage on permeability and F–T resistance of concrete, Fractal Fract. 6 (2022) 113.

[23] A. Standard, C305. Standard practice for

mechanical mixing of hydraulic cement pastes and mortars of plastic consistency, Annu. B. ASTM Stand. (2006).
[24] M.A.Y.A. Bakier, K. Suzuki, P. Khajornrungruang, Study on Nanoparticle Agglomeration During Chemical Mechanical Polishing (CMP) Performance, J. Nanofluids. 10 (2021) 420–430.
[25] V.I. Popkov, Y. Albadi, The effect of co-precipitation temperature on the crystallite size and aggregation/agglomeration of $GdFeO_3$ nanoparticles, Наносистемы: Физика, Химия, Математика. 12 (2021) 224–231.
[26] Q. Li, L. Zhang, S. Wei, Y. Zhang, R. Sun, T. Zhou, W. Bu, Q. Yao, Z. Jiang, H. Chen, Weakly agglomerated α-Al2O3 nanopowders prepared by a novel spray precipitation method, Ceram. Int. 44 (2018) 11374–11380.
[27] R. Pournajaf, S.A. Hassanzadeh-Tabrizi, Polyacrylamide synthesis of nanostructured copper aluminate for photocatalytic application, J. Adv. Mater. Process. 5 (2018) 12–19.
[28] Y.A. Criado, M. Alonso, J.C. Abanades, Kinetics of the CaO/Ca (OH) 2 hydration/dehydration reaction for thermochemical energy storage applications, Ind. Eng. Chem. Res. 53 (2014) 12594–12601.
[29] J. Kariya, J. Ryu, Y. Kato, Reaction performance of calcium hydroxide and expanded graphite composites for chemical heat storage applications, ISIJ Int. 55 (2015) 457–463.
[30] L. Wang, L. Chen, J.L. Provis, D.C.W. Tsang, C.S. Poon, Accelerated carbonation of reactive MgO and Portland cement blends under flowing CO_2 gas, Cem. Concr. Compos. 106 (2020) 103489.
[31] R.L. Frost, S. Bahfenne, J. Graham, Raman spectroscopic study of the magnesium-carbonate minerals—artinite and dypingite, J. Raman Spectrosc. An Int. J. Orig. Work All Asp. Raman Spectrosc. Incl. High. Order Process. Also Brillouin Rayleigh Scatt. 40 (2009) 855–860.
[32] A.L. Harrison, V. Mavromatis, E.H. Oelkers, P. Bénézeth, Solubility of the hydrated Mg-carbonates nesquehonite and dypingite from 5 to 35° C: Implications for CO_2 storage and the relative stability of Mg-carbonates, Chem. Geol. 504 (2019) 123–135.
[33] S.A. Walling, J.L. Provis, Magnesia-based cements: a journey of 150 years, and cements for the future?, Chem. Rev. 116 (2016) 4170–4204.
[34] L. Mo, F. Zhang, D.K. Panesar, M. Deng, Development of low-carbon cementitious materials via carbonating Portland cement–fly ash–magnesia blends under various curing scenarios: a comparative study, J. Clean. Prod. 163 (2017) 252–261.
[35] L. Mo, D.K. Panesar, Effects of accelerated carbonation on the microstructure of Portland cement pastes containing reactive MgO, Cem. Concr. Res. 42 (2012) 769–777.
[36] V.D. Pizzol, L.M. Mendes, L. Frezzatti, H. Savastano Jr, G.H.D. Tonoli, Effect of accelerated carbonation on the microstructure and physical properties of hybrid fiber-cement composites, Miner. Eng. 59 (2014) 101–106.
[37] B.J. Zhan, D.X. Xuan, C.S. Poon, C.J. Shi, Effect of curing parameters on CO_2 curing of concrete blocks containing recycled aggregates, Cem. Concr. Compos. 71 (2016) 122–130.
[38] C. Shi, Y. Wu, Studies on some factors affecting CO_2 curing of lightweight concrete products, Resour. Conserv. Recycl. 52 (2008) 1087–1092.
[39] Y. Sun, P. Zhang, W. Guo, J. Bao, C. Qu, Effect of nano-$CaCO_3$ on the mechanical properties and durability of concrete incorporating fly Ash, Adv. Mater. Sci. Eng. 2020 (2020).
[40] S. Ruan, C. Unluer, Influence of mix design on the carbonation, mechanical properties and microstructure of reactive MgO cement-based concrete, Cem. Concr. Compos. 80 (2017) 104–114.
[41] P. Hou, Y. Cai, X. Cheng, X. Zhang, Z. Zhou, Z. Ye, L. Zhang, W. Li, S.P. Shah, Effects of the hydration reactivity of ultrafine magnesium oxide on cement-based materials, Mag. Concr. Res. 69 (2017) 1135–1145.
[42] R. Polat, R. Demirboğa, F. Karagöl, The effect of nano-MgO on the setting time, autogenous shrinkage, microstructure and mechanical properties of high performance cement paste and mortar, Constr. Build. Mater. 156 (2017) 208–218.
[43] Q. Ye, K. Yu, Z. Zhang, Expansion of ordinary Portland cement paste varied with nano-MgO, Constr. Build. Mater. 78 (2015) 189–193.