LONG-TERM DURABILITY TESTING ON THE MGO-ACTIVATED SLAG CURED IN BRINE

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ABSTRACT

The corrosion of the concrete in the brine environment has been a challenging issue over years. CaO-activated slag was reported to have an improved anti-corrosion property over the ordinary Portland cement, but its shrinkage cracking remained a problem. MgO-activated slag had lower shrinkage and greater potential of improved corrosion resistance. However, its long-term behavior in the brine environment was still unknown. This paper presents an experimental testing on the durability of the MgO-activated slag paste when cured in the brine. Cube samples were prepared and cured in four single salt solutions and three mixed double-salt solutions. Each single salt solution contained one of the four chemicals of NaCl, Na₂SO₄, MgCl₂, MgSO₄. The mixed double-salt solutions were “NaCl + Na₂SO₄”, “NaCl + MgCl₂”, “Na₂SO₄ + MgSO₄”, with various molar ratios. The compressive strength of the MgO-activated slag samples cured in the different solutions was tested at different ages up to 365 days. The experimental results indicated that the MgO-activated slag could hardly sustain the strength after 150 days when cured in the brine solutions. It seemed that $\text{SO}_4^{2-} > \text{Cl}^-$ and $\text{Mg}^{2+} > \text{Na}^+$ in terms of the corrosion damage to the MgO-slag paste. As indicated by the

X-ray diffraction (XRD) and the scanning electron microscopy (SEM) testing, the strength degradation was mainly attributed to the consumption of the CSH in the acid solution (i.e. MgCl_2 or MgSO_4), and the generation of the expansive Aft in the solutions of SO_4^{2-} (i.e. Na_2SO_4 or MgSO_4). Finally, it was recommended that MgO-slag should not be used for the construction of the concrete structures in the salt lake areas.

KEYWORDS: Concrete; Slag; Corrosion; Durability; Brine; Strength

1. INTRODUCTION

As the main construction material all over the world [1-3], concrete has been facing a challenging issue of corrosion especially when used in the offshore structures, or the structures built on saline rich soil. For example, many existing concrete piles in the salt lake area in the west of China [4, 5] were found severely corroded after just 5 years of service time [5-7]. For the offshore structures, the concrete corrosions were observed generally no later than 20 years [6-9]. The damages caused by the concrete corrosion have greatly impeded the local economy development of those areas, and thus the demand for the structural repair and the other anti-corrosion measures are increasing [10-13].

It has been well documented [14-19] that the concrete corrosion was mainly attributed to the chemical degradation of the cementitious material in the brine environment. Ions like Na^+ , Mg^{2+} , Cl^- , SO_4^{2-} , would react with the raw material or the hydration products of the cement, leading to the strength loss of the concrete. It was reported that [14-20] the ordinary Portland cement concrete (OPC) would be destroyed in 1 to 3 years in the salt lake area [20]. This is because [21] SO_4^{2-} would react with the calcium aluminate (CA) in the

concrete, and generate considerable hydrated calcium aluminate sulfate (AFt). AFt is expansive and causes the cracking of the concrete, leading to the strength reduction [7, 22, 23]. High strength concrete (HSC) or high performance concrete (HPC) is denser and more compact than OPC, and thus could delay the penetration of SO_4^{2-} . However, these materials were still found corroded within 7 to 14 years [20].

In addition to the OPC concrete, there are also other types of concrete materials, including high alumina cement concrete (HAC), sulphoaluminate cement concrete (SCC), magnesium oxychloride cement concrete (MOC) and polymer impregnated concrete (PIC). Unfortunately, they also suffer from the corrosion problems. For example, CAH (the hydrate of HAC or SCC) would react with SO_4^{2-} and generate AFt, which would expand and cause cracking of the concrete [24, 25]. The hydrate phase of the MOC was reported [26] unstable when cured in the natural brine environment [26]. PIC presented corrosion-resistance property when cured in the brine [27], but the cost of the PIC is too high to be used in large quantity in the engineering projects [28-30]. In order to prevent the corrosive ions attacking the concrete material, the structural elements were wrapped with anti-corrosion rolls in some projects in the salt lake area [31], but the corrosion still could not be effectively prevented, and the cost of rebuilding was expensive [31].

CaO-activated slag exhibited desirable salt-corrosion resistance in comparison with the other existing cements, when cured in the brine of low concentration (i.e. 10wt.% NaCl solution for 180 days) [17, 32]. However, the engineering application of the CaO-activated slag was limited due to its significant shrinkage in air [33, 34]. If the CaO-activated slag was used for the construction of piles buried in the soil (where the holes of the soil are filled with

brine), the problem of shrinkage should have been avoided. Unfortunately, the generation of the expansive AFt is still inevitable because the SO_4^{2-} in the brine will react with Ca^{2+} and Al^{3+} in the CaO-activated slag. Then the question is, if some other activation agent (without Ca^{2+}) is used in the slag, will it present improved corrosion resistance in the brine?

MgO-activated slag (MgO-slag) was developed in the last decade, and it achieved a higher strength than the CaO-slag as reported in [35-38]. Extensive microstructural investigations revealed that the main hydration products of the MgO-slag were mainly calcium silicate hydrate (CSH), hydrotalcite (Ht), $\text{Ca}(\text{OH})_2$ (CH) and etc. Therefore, if the MgO-slag is used as the cementitious material for the construction of the concrete piles buried in the saline soil containing SO_4^{2-} , the concrete damage by the expansive AFt might be alleviated as there is less Ca^{2+} in the MgO-slag. Surprisingly, there is still no long-term durability testing results of the MgO-slag samples cured in the brine [35-37] in the literature.

This paper presents an experimental work on the long-term strength development of the MgO-slag paste when cured in the brine [35-38]. The effects of different ions in the brine on the strength degradation with time of the MgO-slag samples were investigated. The saturated solutions containing one of the four chemicals (NaCl , Na_2SO_4 , MgCl_2 , MgSO_4) were prepared, and the MgO-slag samples were immersed and cured in each solution for up to 1 year. The strength of the MgO-slag samples at different age was tested to analyze the trend of the strength degradation. The mixed saturated solution of “ $\text{NaCl} + \text{Na}_2\text{SO}_4$ ”, “ $\text{NaCl} + \text{MgCl}_2$ ” and “ $\text{Na}_2\text{SO}_4 + \text{MgSO}_4$ ” were also prepared with various ion molar ratios (e.g. $\text{Cl}^-/\text{SO}_4^{2-}$, “ $\text{Na}^+/\text{Mg}^{2+}$ ”), to study the concentration effects of the different ions on the strength development of the MgO-slag. For comparison purpose, OPC samples were also prepared in

the same brine solutions and the strength at different ages was also tested. Finally, the chemical composition and the microstructure of the cured products were analyzed using the X-ray diffraction (XRD) and the scanning electron microscopy (SEM) respectively. The underlying micro mechanism of the long-term strength development of the MgO-slag cured in brine was discussed and reported.

2. MATERIALS AND EXPERIMENTAL PROGRAM

2.1 Materials

In this paper, MgO-slag was prepared with a mixture of two components, the slag and the MgO powder. The slag was provided by the Beijing Shougang Co. Ltd with a specific surface area of 400 m²/kg. The detailed chemical compositions of the slag and the MgO powder are shown in Table 1 and Table 2, respectively. The slag was also tested using XRD and the pattern is shown in Fig. 1(a). The MgO powder was an industrial material with a tested activity of 40% according to the chemistry and technology of magnesia [39]. The MgO powder was grinded and sieved to the size under 150 μm in diameter. The XRD pattern of the MgO powder is shown in Fig. 1(b). In order to compare with the MgO-slag, the reference cement was also prepared which is normally the main composition of OPC. The reference cement was provided by the China United Cement Co. Ltd. The chemical composition of the reference cement is listed in Table 3, and its mineral composition is presented in Table 4.

The MgO-slag and the reference cement samples were cured in two types of brine solutions, single salt solution and mixed double-salt solution. Four single salt solutions were prepared, with each containing one of the four chemicals NaCl, Na₂SO₄, MgCl₂ and MgSO₄.

The single salt solutions were prepared by mixing NaCl, Na₂SO₄, MgCl₂·6H₂O, MgSO₄·7H₂O with the tap water at 25 °C according to [40]. The chemicals were supplied by the Beijing Sinopharm Chemical Co. Ltd. Three types of mixed double-salt solutions were prepared. Each solution was a mixture of two chemicals with the tap water, e.g. “NaCl + Na₂SO₄”, “NaCl + MgCl₂”, “Na₂SO₄ + MgSO₄”. For each mixed double-salt solution, the molar ratio of the two chemicals was varied. For example, NaCl/Na₂SO₄ ratio was selected as 0.5, 2, 4 and 6. And the ratios of the two solutions of NaCl/MgCl₂ and Na₂SO₄/MgSO₄ changed as 2, 6 and 9. The purpose of changing the molar ratio was to study the effects of the concentration variation of the chemicals on the mechanical degradation of the samples. In addition, different molar ratios represent the concentration change of different ions in the natural environments in China. For example, the concentration variation of Na⁺, Mg²⁺, Cl⁻ and SO₄²⁻ ions in Ge’ermu City in China was reported in [5]. Even in the same city, the concentration of the same ion could vary to a much extent. As reported in [5], the mass content of Na⁺ in the brine could range from 0.09% to 9.47%. Therefore, the selected molar ratios of the mixed salt solutions could well cover the variation of the ions in the natural environment. When preparing the brine solutions, the tap water was added to the chemical powders very slowly, and at the same time carefully stirred with a glass bar. The solutions were ready for use when a little chemical residue was left at the bottom of the container at 25°C. All the containers were sealed during the curing process of the MgO-slag and the reference cement samples.

Table 1 The chemical composition of the slag (wt.%)

CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	Na ₂ O	K ₂ O	SO ₃	MnO	P ₂ O ₅	Cl
44.06	28.72	15.13	0.83	5.34	0.2	0.47	3.81	0.23	0.08	0.06

Table 2 The chemical composition of the MgO powder (wt.%)

MgO	CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	others
81.36	2.11	2.72	0.20	0.33	13.28

Table 3 The chemical composition of the reference cement (wt.%)

Composition	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	Na ₂ Oeq	f-CaO	Loss	Cl ⁻
Content	20.760	4.580	3.270	62.130	3.130	2.800	0.057	0.760	1.860	0.013

Table 4 The mineral composition of the reference cement (wt.%)

Composition	C ₃ S	C ₂ S	C ₃ A	C ₄ AF	total
Content	56.62	19.58	6.36	10.49	93.05

Fig. 1. XRD patterns of (a) the slag; and (b) the MgO powder

2.2 Sample preparation

Cube samples of the MgO-slag and the reference cement were prepared with a dimension of $20 \times 20 \times 20 \text{ mm}^3$. The mix proportion of the MgO-slag was MgO/slag/tap water=1:9:3 (weight ratio), while one part of the reference cement was mixed with 0.24 (weight ratio) part of the tap water to prepare the cube samples. The mix proportions of the MgO-slag and the reference cement were selected to achieve the reasonable strength. During the preparation process, the fresh pastes of the two materials were poured into a steel mold with a dimension

of $20 \times 20 \times 20 \text{ mm}^3$. Then the mold was covered using a plastic wrap, and placed in the lab at an average temperature of about 17°C . The samples of the reference cement were demolded after 1 day, and the MgO-slag samples were demolded after 7 days, when both materials achieved adequate strength for demolding.

After demolding, the samples were immersed and cured in the single salt solutions and the mixed double-salt solutions (as mentioned in Section 2.1) until the specified age. The samples were also immersed and cured in the tap water for the comparison purpose. In each curing tank, the volume ratio between the samples and the liquid solution were 1:5. The curing temperature of all samples was about 17°C . The samples were all immersed in the brine solutions in order to simulate the pile applications, in which the materials were buried underground and immersed in the brine solutions. Since all the samples were immersed and cured in the solutions, the curing humidity was 100%. The demolding time may affect the initial strength of the MgO-slag and the reference cement. However, if the strength at different age was normalized by the initial strength to evaluate the trend of the strength development, the demolding time would have little effect and the strength development in the brine solutions may be mainly attributed to the chemical attack. More details will be discussed in Section 3.

2.3 Experimental testing

(1) Compressive testing

Compression tests were conducted on the samples at the age of 3 days, 7 days, 28 days, 60 days, 90 days, 150 days, 210 days and 365 days. The universal testing machine from Beijing

Gongju Factory was used with a loading capacity of 100 kN. The loading rate was 1 mm/min. At least three samples of the same curing condition were tested for repeating purpose, and the average compressive strength and the corresponding coefficient of variation (COV) were recorded. The dimension of the samples and the procedure of the compressive tests were also adopted by the other researchers [41-43].

(2) X-ray diffraction (XRD) testing

XRD testing was used to analyze the chemical change of the samples. Firstly, the cube samples were dried in an oven at 60 °C until the weight of the samples did not change. Then a little piece was collected from the center of each cube sample. Then the piece was grinded into powder and sieved to the size under 75 μm in diameter. Then this powder was analyzed using XRD machine from PANalytical Empyrean of model P3. The testing parameters were set at 40 kV, 40 mA, Cu/Kα. The powder was scanned at an angle (2θ) ranging between 15 degrees and 65 degrees, at a scanning speed of 0.2 s/step, with a resolution of 0.026 degree/step.

(3) Scanning electron microscope (SEM) analysis

The microstructure of the dried samples was also analyzed using SEM. The cube samples were dried in an oven at 60 °C until the weight of the samples did not change. The SEM instrument was from JEOL Inc., and the model was JSM-7500F. The amplification factor was 300 times.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

3.1 Strength development of the MgO-slag and the reference cement paste in the single salt solutions

The strength development curves of the MgO-slag and the reference cement paste, which were cured in the different single salt solutions, are plotted in Fig. 2(a) and Fig. 2(b), respectively. This work focused on the strength development trend of the MgO-slag and the reference cement paste when cured in various brine solutions, so the initial strength was of less importance when evaluating the strength development trend. Therefore, the “strength ratio (%)” was used as the vertical axis in Fig. 2. The “strength ratio (%)” means, for each curve, the strength at different ages (7, 28, 60, 150, 210, 365 days) was normalized by the strength at 7 days. The absolute compressive strength of the MgO-slag samples cured in the tap water, the saturated solutions of NaCl, Na₂SO₄, MgCl₂, MgSO₄ at the age of 7 days were 4.8 MPa, 9.1 MPa, 14.4 MPa, 3.6 MPa, 9.6 MPa, and the strength of the reference cement at the age of 3 days were 53.2 MPa, 46.6 MPa, 60.1 MPa, 38.9 MPa, 56.3 MPa. The comparison on the absolute strength values in various single solutions will be discussed in the next section. It should be noted that, the age in this paper refers to the absolute time that the samples were immersed in the brine solutions, excluding the demolding time (e.g. 1 day for the reference cement paste and 7 days for the MgO-slag paste). The curves of the MgO-slag paste in Fig. 2(a) were plotted using solid symbols, while the curves of the reference cement paste in Fig. 2(b) were presented with hollow symbols.

It can be seen in Fig. 2(a) that, when cured in the tap water, the strength of the MgO-slag continuously increased up to 365 days (almost 400% increase comparing to the

strength at 7 days). On the other hand, when cured in the single salt solutions, the strength development was different between the Na^+ rich solutions (e.g. NaCl or Na_2SO_4) and the Mg^{2+} rich solutions (MgCl_2 or MgSO_4). For Na^+ rich solutions, a two-stage strength development was observed for the MgO-slag samples. The strength firstly increased upto 150 days, after which the strength drop dramatically. For example, the strength in the Na_2SO_4 solution increased by 150% at 150 days while drop to zero after 210 days, comparing to the strength at 7 days. On the other hand, when cured in the Mg^{2+} rich solutions, the MgO-slag paste totally lost strength after only 28 days. It should be noted in Fig. 2 that, the strength dropped to zero means that the samples were totally damaged (see Fig. 3) after the curing in the corresponding single salt solution, making it impossible to do the compressive testing.

There are two interesting observations in Fig. 2(a). For the first observation, in the Na^+ rich solutions, MgO-slag paste's strength increased in the first stage, but at a lower speed comparing to the samples cured in the tap water. In the second stage, the strength dropped to almost zero. It seems that there are two competing mechanisms which contribute to the two-stage strength development. The first mechanism is the strength build-up mechanism which is the same as the curing process in the tap water. The second mechanism is the corrosion damage due to the salt solution. In the first stage, the curing mechanism was dominant so that the strength kept increasing, though the speed was lowered by the corrosion mechanism. In the second stage after 150 days, the corrosion mechanism overtook the curing mechanism and the strength dramatically dropped. The second interesting observation is that the MgO-slag paste could not develop any strength in the Mg^{2+} rich solutions. It indicates that the corrosion damage in the Mg^{2+} rich solutions may be much more severe than that in the

Na⁺ rich solutions.

The strength development curves of the reference cement paste in various single salt solutions are shown in Fig. 2(b). It is obvious that the reference cement paste could hardly sustain its strength when cured in any single salt solution, though the strength in the tap water increased linearly up to 365 days. Comparing to the curves in Fig. 2(a), it is clear that the reference cement paste is more sensitive to the corrosion damage than the MgO-slag paste when cured in the single salt solutions.

Fig. 2. The strength development curves of (a) the MgO-slag paste and (b) the reference cement paste in different single salt solutions

Fig. 3. The appearance of the MgO-slag paste after 365 days curing in the (a) tap water; (b) single NaCl solution and (c) single Na₂SO₄ solution

3.2 Strength development of the MgO-slag in the mixed double-salt solutions

To further investigate the strength development of the MgO-slag paste, the samples were also cured in three mixed double-salt solutions. They were “NaCl + Na₂SO₄”, “NaCl + MgCl₂” and “Na₂SO₄ + MgSO₄” solutions. The reference cement samples were not tested as they could not sustain the strength in any single salt solution. The strength development curves of the MgO-slag paste in the three mixed double-salt solutions are presented in Figs. 4(a) to (c) respectively. Different from Fig. 2, the absolute strength values were used in Fig. 4 in order to identify which ions play a more important role in the corrosion damage mechanism to the MgO-slag paste.

In Fig. 4(a), the two-stage strength development pattern was observed again for the MgO-slag paste cured in the mixed “NaCl + Na₂SO₄” solution. The turning point was still at the age of 150 days. It is interesting that the strength in the single NaCl solution was always lower than that in the single Na₂SO₄ solution at any age within 150 days. With the increase of the molar ratio of NaCl/Na₂SO₄, the strength curve gradually shifted from Na₂SO₄ curve to the NaCl curve. However, when the age exceeded 150 days, the MgO-slag samples could not sustain any compressive load in the existence of SO₄²⁻. This indicates that the corrosion damage due to SO₄²⁻ was more severe than that caused by Cl⁻.

In Fig. 4(b), the strength curves of the MgO-slag paste cured in the mixed solution of NaCl/MgCl₂ with various molar ratios were compared. It seems that, the Mg²⁺ plays a more dominant role than Na⁺ in terms of introducing the corrosion damage to the MgO-slag paste. With the increase of the molar ratio of NaCl/MgCl₂ from 2 to 9, the strength curve shifted from the curve of the single NaCl solution to that of the single MgCl₂ solution. This

argument is further supported by the observation in Fig. 4(c). In other words, when the MgO-slag paste was cured in the mixed “Na₂SO₄ + MgSO₄” solution, the strength would decrease with the increase of the Mg²⁺ concentration. It is obvious in Fig. 4(c) that, the strength curve gradually dropped from the curve of the single Na₂SO₄ solution to that of the single MgSO₄ solution with the decrease of their molar ratio.

Fig. 4. The strength development curves of the MgO-slag paste in the mixed double-salt solutions of the (a) NaCl+Na₂SO₄; (b) NaCl+MgCl₂ and (c) Na₂SO₄+MgSO₄

Considering the results in Fig. 4, it can be concluded that $\text{SO}_4^{2-} > \text{Cl}^-$, and $\text{Mg}^{2+} > \text{Na}^+$ in terms of the corrosion damage to the MgO-slag paste. For $\text{SO}_4^{2-} > \text{Cl}^-$, this may be because the expansive Aft is more likely to be generated when more SO_4^{2-} exists, causing cracking of the MgO-slag paste. This argument is evidenced by the appearance of the MgO-slag paste cured in the mixed “NaCl + Na₂SO₄” solution in Fig. 5. It can be seen in Fig. 5 that, the MgO-slag paste were damaged more severely with the increase of the SO_4^{2-} concentration in the mixed solution. For $\text{Mg}^{2+} > \text{Na}^+$, this is because the pH of the MgCl₂ or the MgSO₄ solution is lower than 7 (acid). However, the hydrate of the MgO-slag paste is alkaline. Therefore, the MgO-slag paste could not be stable in the solution of MgCl₂ or MgSO₄.

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294 Fig. 5. The appearance of the MgO-slag samples after 365 days curing in the (a) tap water; (b)

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NaCl/Na₂SO₄= 6 and (c) NaCl/Na₂SO₄ = 4

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297 4 CHEMICAL AND MICROSTRUCTURAL CHARACTERIZATION OF THE

298 MGO-SLAG HYDRATE

299 4.1 XRD testing results

300 The XRD patterns of the MgO-slag paste after 356 days curing in the single NaCl solution,

301 mixed “NaCl + Na₂SO₄” solution with a molar ratio of 4 and the single Na₂SO₄, are presented

302 in Figs. 6(b) to (d), respectively. The XRD pattern of the MgO-slag paste cured in the tap

303 water [36] was also presented in Fig. 6(a) for comparison purpose. This is to study the

304 chemical change in the MgO-slag hydrate due to the variation of the Cl⁻ and SO₄²⁻

305 concentrations. For the NaCl/Na₂SO₄ mixed solution, the molar ratio of 4 was selected,

306 because the samples cured in the NaCl/Na₂SO₄ solution with other molar ratios showed the

307 same trend of the mechanical degradation (see Fig. 4a).

308 It can be seen in Fig. 6(b), when cured in the single NaCl solution, the hydration

309 products of CSH, CH, Ht and MgCO₃ were observed. CSH, CH and Ht are the typical

310 hydration products of the MgO-slag when cured in the tap water (Fig. 6a [37]). MgCO₃

should come from the industrial raw material of the MgO powder. The hydration products of the MgO-slag when cured in the mixed “NaCl + Na₂SO₄” solution (see Fig. 6c) were almost the same as those in the single NaCl solution (see Fig. 6b). However, when cured in the single Na₂SO₄ solution, one more hydration product was observed in Fig. 6(d), which was AFt. AFt contained five chemical elements (Ca, S, Al, O and H), with S from the solution of Na₂SO₄, and Ca, Al from the slag.

It is known that the strength of the MgO-slag paste is mainly contributed by the CSH, while the CH, Ht, AFt and MgCO₃ are dispersive particles. As indicated by the XRD patterns in Fig. 6, the intensity of the CSH peaks is very low [36] in the brine solutions, which was the main reason why the MgO-slag dramatically lost strength after 365 days in the single and mixed solutions. Another reason of the strength loss was due to the generation of the expansive AFt with the existence of SO₄²⁻ (see Fig. 6d). These XRD results support the arguments on the strength degradation mechanisms in Section 3.2.

It should be noted that, there was an unknown hydrate corresponding to the peak X in Fig. 6. XRD patterns were analyzed using the most updated database in the software of Jade 6.5 with a PDF card of 2004. It seems that X could only be generated with the existence of Cl⁻ because it disappeared in Fig. 6(d) when there was no Cl⁻. Although the chemical composition and its microstructure are unknown, the sharp peak of X suggests that it would be a crystal rather than an amorphous material [44]. Therefore, its existence would not violate the above arguments on the strength degradation mechanism due to the decreasing of CSH and the generation of the expansive AFt.

Fig. 6. XRD patterns of the MgO-slag samples after 365 days curing in the (a) tap water [36]; (b) single NaCl solution; (c) mixed NaCl/Na₂SO₄=4 and (d) single Na₂SO₄ solution

4.2 SEM results

The microstructure of the MgO-slag **paste** was analyzed using the SEM after 365 days curing in the three solutions: the single NaCl solution, mixed “NaCl + Na₂SO₄” solution with a molar ratio of 4, and the single Na₂SO₄ solution. The SEM images (with a magnification of 300 times) of the MgO-slag samples in the three solutions are shown in Figs. 7(b) to (d), respectively. The SEM image of the MgO-slag **paste** cured in the tap water [36] was also presented in Fig. 7(a) for comparison purpose.

The CSH can be clearly observed in Fig. 7(a) when the MgO-slag paste was cured in the tap water, whereas the CSH disappeared when the MgO-slag paste was cured in the solutions with NaCl or Na₂SO₄ (Figs. 7b to d). In addition, extensive acicular crystals of the AFt could be observed in Fig. 7(d) with the increase of SO₄²⁻ in the solution. These SEM observations again provided further microstructural evidences, supporting the arguments that, the damages to the MgO-slag paste were due to the decreasing of the CSH and the generation of the expansive AFt.

Fig. 7. Representative SEM images of the MgO-slag paste after 365 days curing in the solution of the (a) tap water [36]; (b) single NaCl solution; (c) mixed NaCl/Na₂SO₄=4 and (d) single Na₂SO₄ solution

5. CONCLUSIONS

This paper investigated the long-term behavior of the MgO-slag paste when cured in the single salt solutions and the mixed double-salt solutions. Four single salt solutions were selected including NaCl, Na₂SO₄, MgCl₂, and MgSO₄. Three mixed double-salt solutions were “NaCl + Na₂SO₄”, “NaCl + MgCl₂”, and “Na₂SO₄ + MgSO₄” with various molar ratios. The strength development curves of the MgO-slag paste up to 365 days were developed when cured in these different solutions. The mechanisms of the strength degradation were revealed by using the chemical analysis with XRD and the microstructural investigation with SEM. Based on the findings in this study, the following conclusions can be drawn:

- (1) When cured in the Na⁺ rich single salt solution (i.e. NaCl or Na₂SO₄), the MgO-slag paste could develop strength upto 150 days, after which the strength decreased gradually and dropped to zero after 1 year. When cured in the Mg²⁺ rich solutions (i.e. MgCl₂ or MgSO₄), the MgO-slag paste could not develop any strength after 7 days.
- (2) The results of the single salt solution and the mixed double-salt solution indicated that, SO₄²⁻ > Cl⁻ and Mg²⁺ > Na⁺ in terms of the corrosion damage to the MgO-slag paste.
- (3) The corrosion damage to the MgO-slag could be caused by two reasons. One was the consumption of the CSH in the acid solution (i.e. MgCl₂ or MgSO₄), and the other was the generation of the expansive AFt in the solutions of SO₄²⁻ (i.e. Na₂SO₄ or MgSO₄).
- (4) The underlying strength degradation mechanisms of the MgO-slag paste were supported by the chemical analysis using XRD and the microstructural investigation using SEM. It was observed that, with the increase of SO₄²⁻, the CSH gradually disappeared in the hydration products and a considerable amount of the expansive AFt was generated.

MgO-slag contains much less Ca^{2+} in the chemical and mineral compositions in comparison to the cement and the CaO-slag. Therefore, it was expected that the hydration products of MgO-slag would contain much less Aft, which would contribute to the improved durability of the MgO-slag concrete structures in the salt lake area. This was the motivation of the current study on the long term durability performance of MgO-slag when cured in the brine. Unfortunately, the experimental results indicated that the durability of the MgO-slag paste was poor when the corrosion ions existed (i.e. Na^+ , Mg^{2+} , Cl^- , SO_4^{2-}) in the curing environment. Therefore, it is recommended that MgO-slag should not be used for the construction of the concrete structures in the salt lake areas.

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