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Simultaneous effect of granite waste dust as partial replacement of cement and magnetized water on the properties of concrete exposed to NaCl and H_2SO_4 solutions

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HIGHLIGHTS

- Magnetized water significantly improved the mechanical and durability properties of concrete.
- Using granite waste dust up to 10% as partial cement replacement improved the compressive strength of concrete.
- This is true regardless of the curing process: in lime-saturated water and after exposure to aggressive solutions.
- Replacing cement with higher contents of granite waste dust leads to lower mechanical and durability properties of concrete.

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ABSTRACT

The aim of this study is to investigate the simultaneous effect of granite waste dust (GWD) as partial replacement of cement (PRC) and magnetized water (MW) on the mechanical and durability properties of concrete specimens exposed to two aggressive environments (NaCl and H_2SO_4 solutions). For this aim, 10 concrete mixes with different GWD ratios (0%, 5%, 10%, 15% and 20%) were prepared using tap water (TW) and MW. The specimens were first cured in lime-saturated water for a duration of 28 days and then they were exposed to 5% by weight NaCl and H_2SO_4 solutions for a period of 91 days. A number of tests such as compressive strength, resistance to acid attack, water absorption, open circuit potential (OCP) were performed. The results showed that the mechanical and durability properties of concrete improved by using MW, regardless of the GWD incorporation ratio. It was also found that using high amounts of GWD leads to lower strength and durability performance of the specimens due to the reduction of cement content and a more porous microstructure, regardless of the water type used.

1. Introduction

Nowadays, sustainability is considered as one of the most interesting topics in different fields of knowledge such as civil and environmental engineering around the world [1]. One of the main aims of sustainability is to use less natural resources especially in the construction industry. To do so, many studies have been recently carried out in the field of construction industry to minimize the use of natural resources [2–4]. Concrete is considered the most used material in the construction industry [5,6]. Cement which is manufactured principally by heating chalk or limestone to very high temperatures is the binder and main component of a concrete mix and is responsible for 8% of the global CO_2 emission [7]. Therefore, in recent years, a great number of investigations have been carried out to decrease the environmental impacts of the concrete industry by replacing cement with different types of waste materials such as granite and marble waste dust [4,8–12]. Some industries, such as the mining and processing industries of granite stones, are responsible for producing a large amounts of granite waste dust (GWD), which is spread by wind in the surrounding area and causes adverse effects on the environment [4]. Thus, in recent years, GWD and granite aggregates have been used in several different products such as concrete pavers, infiltration

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materials and as natural aggregates or cement replacements to produce concrete mixes in order to decrease their environmental impacts [11,13–15].

Raman et al. [16] reported that the use of granite powder as replacement of river sand to produce high-strength concrete mixes with rice husk ash is practical and can improve the properties of the produced concrete mixes. In an investigation conducted by Hamza et al. [17], it was reported that concrete bricks produced with up to 40% granite waste are suitable for structural applications based on the Egyptian code requirements. The results of Divakar et al. [18] showed that using GWD as partial replacement of fine aggregates up to 35% improved the strength of the produced concrete mixes. The results of Flexikala and Partheeban [19] revealed that using GWD as partial substitution of river sand leads to better mechanical properties of the concrete mixes. The results also showed that the concrete mixes produced with GWD displayed a similar shrinkage behaviour to the controlled mix. Vijayalakshmi et al. [20] reported that there are positive effects on the durability and strength properties of concrete mixes from utilizing GWD as replacement of river sand. The results of Li et al. [21] show that using GWD as paste replacement or addition significantly reduced the cement content in the mortar mixes. The results also show that using 25% GWD as paste replacement improved the compressive strength of the mortar mixes by about 12%. Mashaly et al. [3] reported that the use of 25% GWD as paste replacement to produce mortar and concrete mixes led to a negligible decline of the mechanical and durability properties compared to an ordinary Portland cement mix.

Ghorbani et al [4] reported that the use of GWD up to 10% for concrete production improves the mechanical and durability properties of concrete mixes. The results showed that the use of GWD as partial replacement of cement (PRC) enhances the corrosion resistance of the steel rebars embedded in reinforced concrete elements [4,8]. Abd Elmoaty [22] realized that replacing 5% of the cement with GWD improved the mechanical and corrosion resistance characteristics of the produced concrete mixes. The results of Aarthi and Arunachalam [23] showed that the use of GWD in concrete production improved the acid resistance and chloride ingress of the concrete mixes. Investigation by Ramos et al. [24] revealed that the concrete mixes with GWD were denser than the control mixes, which resulted in a better durability properties without significantly affecting the fresh and hardened properties. It was also reported that the use of GWD as PRC (up to 7.5%) improved the durability of concrete without effecting their fresh and hardened properties [25]. It was reported that the use of GWD as PRC at replacement ratio of 20–50% had a negative effect on the compressive strength of concrete mixes, while the effect on the tensile strength was negligible [15].

Water has an important role on the characteristics of cementitious materials and can have a significant impact on the fresh and hardened properties of the materials. Consequently, several studies have been carried out lately to study the impacts of water on the performance of concrete structures [26–28]. In recent years, MW has been used in concrete production to improve its fresh, hardened and durability characteristics [26,27,29–38]. Hendricks Anton Lorenz was the first one to find that, by circulating water through a permanent magnetic field at a constant speed, MW with a different chemical structure from that of regular tap water can be produced [29].

After the magnetization process of TW, hydrogen bonds between the water molecules causing the water molecules to break apart clusters of about 100 water molecules [30]. As result of this phenomena, the size and the number of clusters reduces and consequently the viscosity and surface area of the water increases, which results in a higher activity of the water molecules [34,39,40]. The effect of magnetic field on the structure of water clusters as they pass through a magnetic field has been shown in Fig. 1 [26].

It has also been reported that, due to lower surface tension of MW compared to TW, a thinner layer of water will be formed around the cement particles, which leads to a much easier penetration of water molecules into the cement matrix [33,35]. This phenomenon can be a possible explanation for the enhancements in the fresh, hardened and durability properties of cementitious materials produced with MW [26,27,29–37]. The results of Gholhaki et al. [31] showed that using MW to produce self-compacting concrete (SCC) enhanced the fresh properties (workability) of the concrete mixes. Bharath et al. [41] concluded that the workability of concrete mixes with copper slag incorporated as PRC improved by about 50% when MW was used. Studies by Su and Wu [34] and Su et al. [35] revealed that the compressive strength of specimens produced with MW in the presence of fly ash and blast-furnace slag increased about 10–23% compared to the controlled mix . Ghorbani et al [26,30] reported that the use of MW to produce foam concrete specimns improved the stability and mechanical properties of the specimens. It was also reported that the fresh and hardened characteristics of SCC mixes reinforced with different contents of steel fibres improved by using MW [27]. An investigation conducted by Wei et al. [32] showed that concrete mixes produced with MW displayed a lower early-stage shrinkage than that of the controlled mix. Ghods [42] and Ahmed [33] also reported improvements in the mechanical properties of concrete mixes as a result of using MW in the presence of nano silicate and nano alumina, respectively. Ghorbani et al. [29] showed that the acid resistance of concrete specimens improved by using MW. Barham et al. [37] investigation showed that concretespecimens produced with MW displayed a higher bond strength than the control specimens for different contents of silica fume.

As revealed by the literature review, despite the investigations carried out so far to study the effect of MW on concrete mixes, no research has been done to study the effect of MW on the concrete mixes with different amounts of GWD as PRC. Therefore, to investigate this effect, several tests were carried out to study the mechanical and durability properties of the produced concrete mixes exposed to two aggressive environments consisting of NaCl and H_2SO_4 solutions.

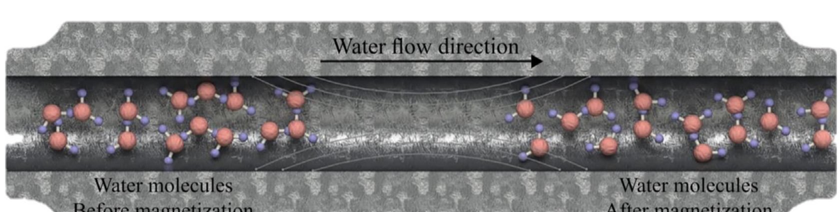

Fig. 1. Effect of magnetic field on water molecule clusters [26].

2. Experimental study

2.1. Materials

To produce the concrete specimens, cement, GWD, water (TW or MW), fine and coarse aggregates were blended in a drum mixer. Portland cement (type II) produced by Zaveh cement company, fine aggregate (natural river sand) with a size of 0.3 to 4.75 mm, and coarse aggregate (crushed limestone) with a size of 4.75 to 25 mm were used to make the concrete specimens. The Portland cement used in this study had a specific gravity of 3.2 g/cm^3. The particle size distribution and chemical composition of the cement are given in Fig. 2 and Table 1, respectively.

The GWD used in this study as PRC to produce concrete mixes was acquired from a granite stone factory nearby. In order to prevent changes in the W/C ratio, the collected GWD was first oven dried at temperature of 105 °C. The specific gravity of GWD was determined as 2.61 g/cm^3. To obtain more information about the GWD's chemical composition, a XRF test was conducted.

The chemical composition of the GWD used in this study is displayed in Table 1, which indicates that silica and alumina constitute a significant portion of GWD. Additionally, the particle size distribution of GWD is shown in Fig. 2. The aggregates (fine and coarse) were collected from local resources. The particle size distribution and physical properties of fine and coarse aggregate are illustrated in Tables 2 and 3, respectively.

In order to produce MW, a magnetic field with a magnitude of 0.65 T was used and TW was circulated through it to achieve the required magnetic features. As indicated in Fig. 3, the used permanent magnet is 200 mm in length with an internal diameter of 32 mm and an external diameter of 55 mm. The number of TW circulations through the magnet and its flow speed can significantly affect the obtained MW; thus, to achieve the best results, a flow speed of 0.75 m/s and 10 rounds of circulation were performed according to previous research [27,31].

To evaluate the performance of steel rebars embedded in reinforced concrete specimens, a steel rebar with 16 mm diameter (A615) was placed in the middle of the reinforced specimens to be exposed to adverse conditions (H_2SO_4 and NaCl solutions).

2.2. Experimental design

In order to study the effect of GWD with different ratios (0%, 5% 10%, 15%, and 20%) as PRC and MW on the mechanical and durability characteristics of the concrete specimens, firstly, the mechanical properties of the specimens at several curing ages cured in lime-saturated water and exposed H_2SO_4 and NaCl solutions were investigated. Then, the durability behaviour of the specimens and the corrosion resistance of embedded steel rebars in the reinforced specimens exposed to 5% by-weight of H_2SO_4 and NaCl solutions were studied. For comparing, five concrete mixes with the same mix proportions were cast with MW.

To prepare the concrete specimens, the raw materials (coarse and fine aggregates, cement, and GWD) were first put inside a drum mixer and blended for about two minutes. Then, water (TW or MW) was added in the drum mixer to achieve a homogenous mix. Afterwards, the obtained concrete mix was poured in plastic moulds and vibrated. Specimens were demoulded after 24 h and placed in lime-saturated water for further curing (28 days). The mix proportions of the concrete mixes are shown in Table 4.

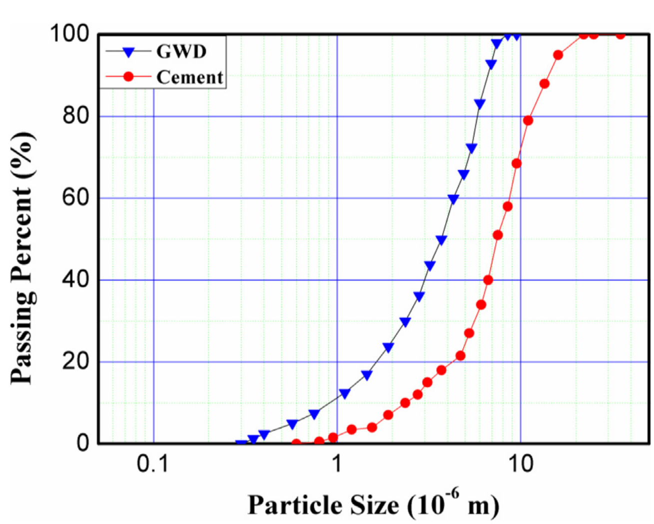

Fig. 2. Particle size distribution of GWD and cement [3].

2.3. Testing

2.3.1. Compressive strength

To evaluate the compressive strength of concrete, cylinder specimens (150 × 300 mm) cured in lime-saturated water were tested according to ASTM C39 at different testing days. For each testing day, three specimens were tested after 7 and 28 days of curing and their mean value was reported as the compressive strength of the mix. In order to determine the compressive strength of specimens exposed to aggressive environments, subsequent to the 28-day lime-saturated water curing, they were placed in 5% by-weight H_2SO_4 and NaCl solutions, separately. The specimens were tested after 7, 28 and 70 days of exposure to the solutions.

2.3.2. Mass loss

In order to examine and study the resistance of concrete specimens to acid attack, the mass loss percentage of three cubic specimens (100 mm) from each mix was calculated weekly and their mean value was reported. In order to keep the pH of the acid solution constant, the acid solution was monitored and refreshed weekly. Every week, the specimens were taken out of the acid solution, washed with TW to detach the chemical products resulting from the acid reaction. Prior to the mass loss measurements, the specimens were kept at the room temperature for 40 min to be dried and then were weighed to measure their mass loss. The mass loss percentage of each specimen was calculated based on the equation described by Ghorbani et al. [4].

2.3.3. Water absorption

To determine the water absorption of concrete specimens according to ASTM C642, three cubic (100 mm) specimens were prepared for each of the concrete mixes. The water absorption of the specimens was tested 7 and 28 days after immersing in lime-saturated water. The water absorption of each mix was reported as the mean value of the three specimens.

2.3.4. Open circuit potential (OCP)

One of the simplest measurements to evaluate the corrosion state of steel rebars in reinforced concrete is the OCP method [43], which was performed according to ASTM C 876. In order to evaluate the corrosion performance of steel rebars inside the specimens using OCP method, cylindrical specimens (100 × 200 mm) were used and a 200 mm long steel rebar with a diameter of 16 mm was placed in the middle of each specimen [7]. After curing the specimens for 28 days in lime-saturated water, the corrosion performance of the steel rebars was evaluated by exposing the specimens to 5% by weight NaCl and H_2SO_4 solutions. The OCP measurements were conducted for a period of 98 days (28 days

Table 1
Chemical composition of cement and GWD [3].

Material	Chemical composition (%)									
	SiO_2	CaO	Al_2O_3	Fe_2O_3	MgO	SO_3	K_2O	Na_2O	Cl	LOI
Cement (type II)	21.4	63.6	4.5	3.5	2.1	2.5	0.5	0.5	0.07	1.9
Granite	70.2	3.7	15.8	1.9	0.6	0.6	3.7	2.1	0.02	1.6

Table 2
Sieve analysis data of the coarse and fine aggregates [3].

Coarse aggregate	Sieve size (mm)	Passing percentage (%)
	37.5	100
	25	91
	19	61.50
	12.5	23
	9.5	5.50
	4.75	0
Fine aggregate	4.75	100
	2.36	83.50
	1.18	58.25
	0.6	28.75
	0.3	4.75
	0.15	0.60
	0.075	0.05

Table 3
Physical properties of the coarse and fine aggregates [3].

Properties	Coarse aggregates	Fine aggregates
Water absorption (%)	1.75	3.75
Moisture content (%)	0.70	2.65
Relative density	2.70	2.63
Oven dry density (kg/m^3)	1625	1660
Fineness modulus		3.24

in lime-saturated water and 70 days in 5% by weight NaCl and H_2SO_4 solutions). A saturated calomel electrode (SCE) was used as a reference electrode for the OCP measurements.

3. Results and discussion

3.1. Compressive strength

3.1.1. Compressive strength of concrete cured in lime-saturated water

The 7 and 28 days compressive strength results of the concrete specimens with different ratios of GWD as PRC (up to 20%) produced with either TW or MW are illustrated in Fig. 4. The results showed that incorporating GWD does not drastically affect the mechanical properties of the concrete specimens relative to the control specimens. In other words, using GWD seems to be an effective way of producing a structural environmentally friendly concrete. As shown in Fig. 4, using GWD up to 10% improved the compressive strength of the specimens regardless of the water type used to produce them. This result is consistent with previous researches that reported an improvement of the mechanical properties of concrete mixes using GWD up to 10% as PRC [1,4,8].

The improvement in the compressive strength of the specimens with GWD may be justified by an enhancement of the hardened density of the interfacial transition zone product as result of the pore filling effect of GWD fine particles. This can also explain the trends in the compressive strength of the specimens exposed to NaCl solution. The increment in compressive strength of the specimens with 10% GWD as PRC after 7 and 28 days relative to the control specimens was about (8.3%, 17.9%) and (13.3%, 18.6%), respectively, for the specimens produced with TW and MW.

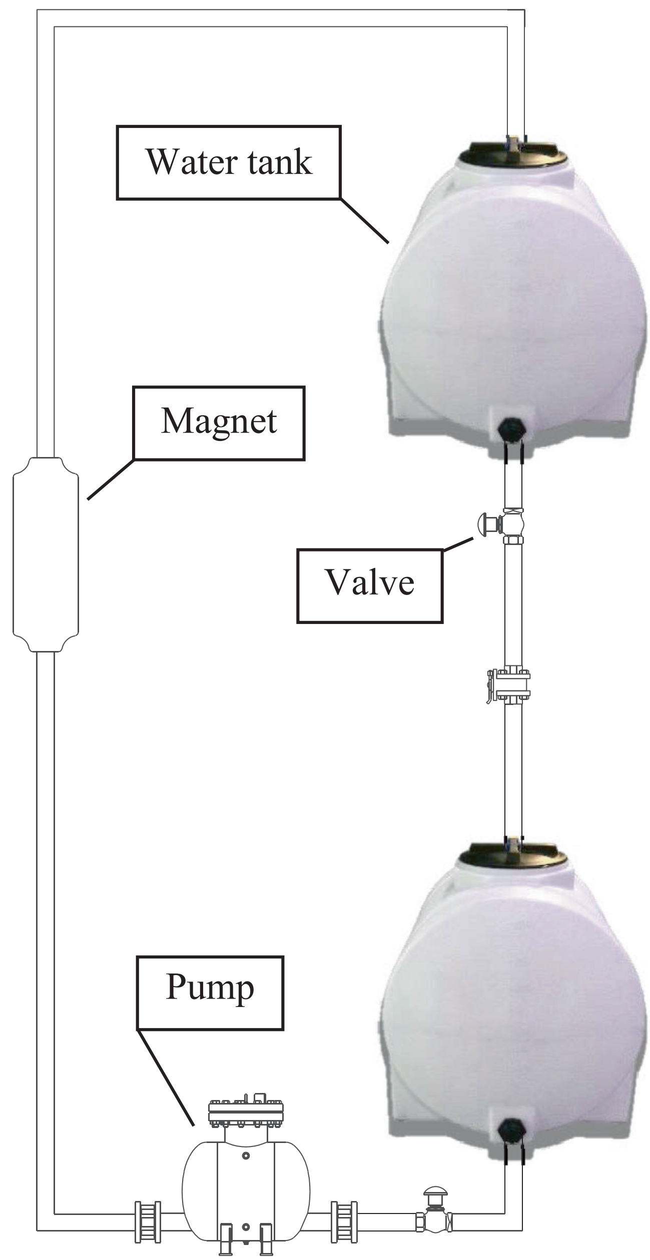

Fig. 3. Magnetic water generating machine [28].

On the other hand, the compressive strength results showed that using GWD with replacement ratios higher than 10% leads to lower compressive strength of the specimens compared to the controlled ones regardless of the water used to produce them. This can be attributed to the level of reduction in the binder (cement) content of the matrix, as reported previously [4,8,15,24]. This also explains the trend in the compressive strength of the specimens exposed to a NaCl solution.

Table 4
Composition of the concrete mixes.

Mix No.	Water Type	Composition (kg/m^3)					
		Granite (%)	Granite (kg)	Cement (kg)	Water (kg)	Fine* (kg)	Coarse** (kg)
1	Tap water	0	0	400	200	715	1000
2		5	20	380	200	710	995
3		10	40	360	200	710	995
4		15	60	340	200	705	990
5		20	80	320	200	700	990
6	Magnetized water	0	0	400	200	715	1000
7		5	20	380	200	710	995
8		10	40	360	200	710	995
9		15	60	340	200	705	990
10		20	80	320	200	700	990

*Fine aggregates **Coarse aggregates

The results showed that the specimens with 20% GWD produced with TW or MW showed lower compressive strength of (20.8%, 21.1%) and (18.4%, 16.6%), respectively, compared to the controlled specimens after curing for 7 and 28 days.

As indicated in Fig. 4, for all of the replacement ratios, the compressive strength of the specimens produced with MW was higher than that of the specimens with TW. This result is in accordance with those of previous studies that reported an enhancement of the mechanical characteristics of concrete mixes produced with MW [26,27,29]. The higher specific area of MW compared to TW may justify the higher compressive strength of the specimens produced with MW. It has been previously reported that passing water through a magnetic field causes the water clusters to break apart and as a result the number of molecules gathered in a water cluster significantly declines [29,40]. Consequently, the activity of water molecules increases, which leads to a more considerable number of interactions between them and the cement particles during the hydration process [30,33,36]. This also explains the trend in the compressive strength of the specimens exposed to NaCl solution. As seen in Fig. 4, the specimens produced with MW and 0%, 5%, 10%, 15% and 20% GWD as PRC showed an improvement of 7%, 8%, 8%, 10%, and 11%, respectively, of the compressive strength after 28 curing days relative to the specimens with TW. The results also showed that the compressive strength of all specimens with either TW or MW increases as curing continued, however, the rate of increase varies.

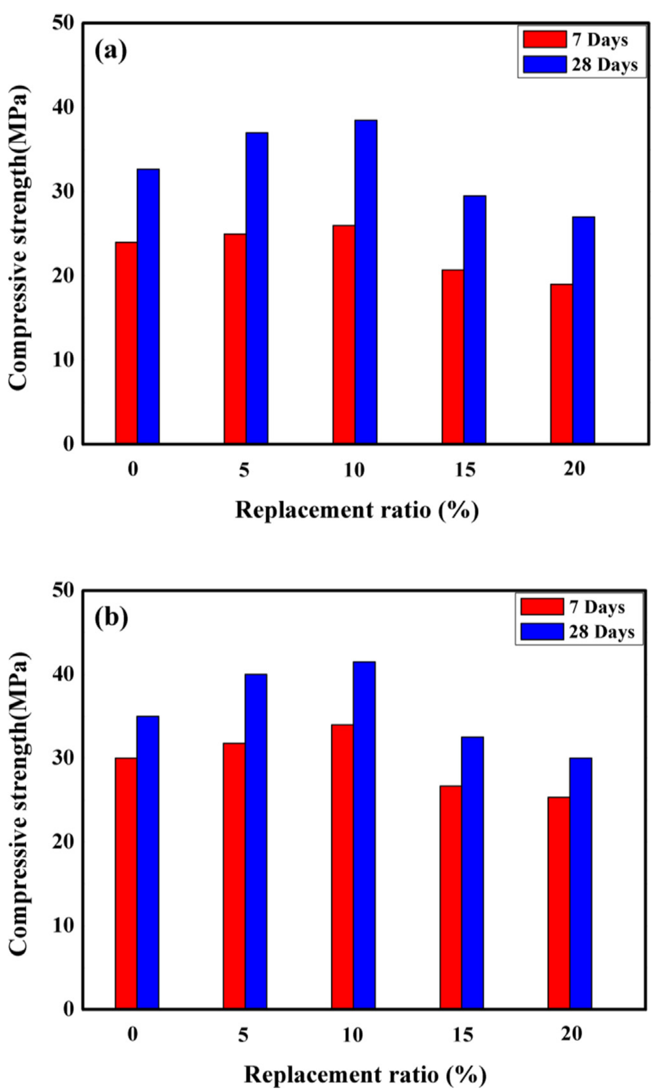

Fig. 4. Compressive strength of concrete mixes with GWD as PRC using (a) tap water and (b) magnetized water after 7 and 28 days of curing in lime-saturated water.

3.1.2. Compressive strength after exposure to H_2SO_4 solution

The compressive strength results of the specimens exposed to a 5% by weight H_2SO_4 solution are displayed in Fig. 5. The specimens were kept in an acid solution for a total duration of 70 days and were tested after 7, 28, and 70 days of acid exposure subsequent to the 28 days curing in lime-saturated water. As indicated in Fig. 5, for all testing days, the compressive strength of the specimens decreases after exposure to the acid solution, however, the rate of decrease depends on the time of exposure to the acid solution. The compressive strength reduction of the specimens may be justified by the reaction of sulphuric acid with $Ca(OH)_2$ [44]. In addition, extensive formation of gypsum in the regions close to the surfaces is expected when the specimens are exposed to a (H_2SO_4) acid solution [45]. The results also showed that, for all the specimens produced with either MW or TW and different replacement ratios of GWD, the largest loss in compressive strength was seen after 70 days of exposure to the acid solution.

As seen in Fig. 5, the specimens with MW displayed a higher compressive strength than the controlled specimens produced with TW at all testing ages regardless of the GWD incorporation ratio. This means that using MW to produce concrete leads to a more resistant material to acid attack. As reported, the durability characteristics of concrete mixes significantly depend on the porosity of their structure, the lower porosity of a concrete enhances its durability characteristics [8,46]. It has been reported that the use of MW to produce concrete specimens results in a denser structure and consequently lower number of pores in the concrete structure [30,33,41]. The results showed that the specimens

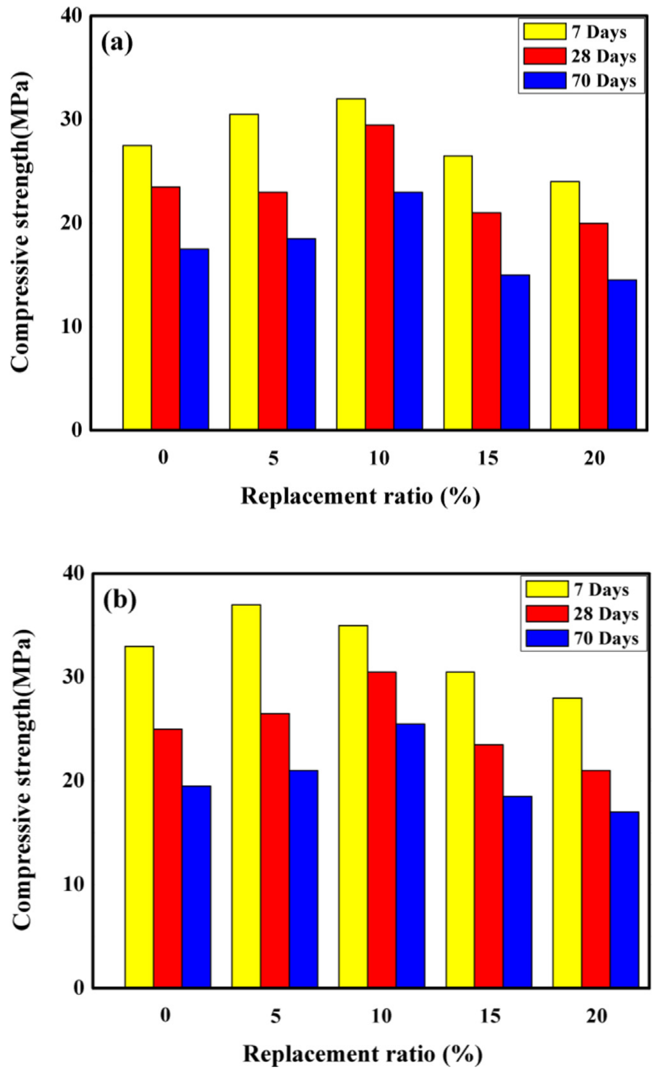

Fig. 5. Compressive strength of concrete mixes with GWD as PRC using (a) tap water and (b) magnetized water after 7, 28 and 70 days of exposure to a 5% by weight H_2SO_4 solution.

with MW and 0%, 5%, 10%, 15% and 20% GWD as PRC had a higher compressive strength by (20%, 6.5%, 11.50%), (21.5%, 15.50%, 13.50%), (9.5%, 3.5%, 11%), (15%,12%, 23.50%) and (16.50%, 5%, 17%), respectively, after 7, 28 and 70 days of acid exposure relative to the specimens with TW.

As seen in Fig. 5, for specimens with either TW or MW, replacing cement with GWD up to 10% leads to a better acid resistance than that of the controlled specimens. This improvement may be related to the enhanced bonding capability and micro-filler action of tiny GWD particles, which results in a denser and consequently better microstructure of the concrete matrix. On the other hand, the results showed that, for specimens with either TW or MW, replacing cement with higher amounts of GWD (>10%) leads to lower acid resistance. This lower compressive strength maybe justified by the poorer microstructure of the concrete matrix by replacing higher amounts of GWD. It has also been reported that using 7.5%, 10.0% and 15.0% GWD as PRC leads to a more porous concrete structure [22]. The results showed that the concrete specimens with 20% GWD showed the lowest compressive strength at all testing ages after exposure to the H_2SO_4 solution, regardless of the water type used to produce them. The specimens with 20% GWD as PRC produced with TW and MW lower compressive strength by (13%, 15%, 17%) and (15%, 16%, 13%), respectively, relative to the controlled specimens after 7, 28 and 70 days exposure to the H_2SO_4 solution.

3.2. Compressive strength after exposure to NaCl solution

The compressive strength results of the specimens with different replacement ratios of GWD as PRC (up to 20%) produced with either TW or MW after 7, 28 and 70 days of exposure to 5% by weight of NaCl solution are shown in Fig. 6. For all of the specimens produced with either TW or MW, their compressive strength increases as the exposure time to the NaCl solution becomes longer. Therefore, it can be concluded that, in contrast with the results of the acid solution, the submersion of specimens in NaCl solution does not have a significant negative effect on their compressive strength. In other words, the chloride attack is not as aggressive as the acid attack and does not deteriorate the concrete structure or even decrease its compressive strength. The results also showed that as the curing age continues the strength development rate of the concrete mixes declines compared to the first days of curing, since the hydration products reach a given level.

As seen in Fig. 6, for specimens produced with either TW or MW, thecompressive strength is higher than that of the controlled

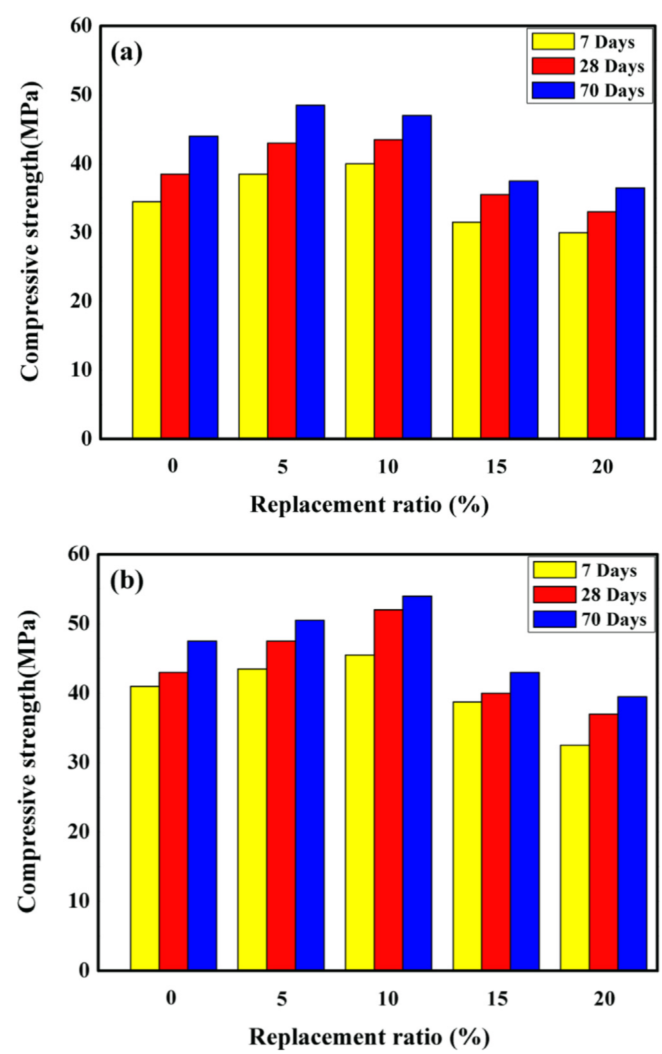

Fig. 6. Compressive strength of concrete mixes with GWD as PRC using (a) tap water and (b) magnetized water after 7, 28 and 70 days of exposure to a 5% by weight NaCl solution.

specimens at all testing ages when using up to 10% GWD as PRC. The specimens produced with 5% and 10% GWD as PRC using TW and MW displayed a higher compressive strength by (11.5%, 12%, 10.5%), (16%, 13%, 7%), (6%, 10.5%, 6.5%) and (11%, 21%, 14%), respectively, compared to the controlled specimens after 7, 28 and 70 days of exposure to NaCl solution.

On the other hand, using higher amounts (>10%) of GWD as PRC to produce the specimens with either TW or MW results in lower compressive strength than that of the controlled specimens. As indicated in Fig. 6, the specimens with 20% GWD produced with either TW or MW displayed the lowest compressive strength of all the specimens at all testing ages.

The results also showed that, similarly to those in Fig. 4, all specimens with MW displayed a higher compressive strength than that of the specimens with TW, regardless of the GWD's content. This means that using MW to produce concrete leads to a better structure and consequently higher compressive strength when exposed to a NaCl solution. The specimens produced with 0%, 5%,10%, 15% and 20% GWD as PRC and MW displayed a higher compressive strength by (19%, 12%, 8%), (13%, 10.50%, 4%), (14%, 19.50%, 15%), (23%, 13%, 14.50%) and (8.50%, 12%, 8%), respectively, after 7, 28 and 70 days of exposure to the NaCl solution.

3.3. Water absorption

Fig. 7 shows the water absorption of the concrete specimens produced with either TW or MW and GWD as PRC after 7 and 28 days of curing. As indicated in Fig. 7, using up to 10% GWD as PRC leads to a slightly lower water absorption after 7 and 28 days of curing, regardless of the water type used to produce the specimens. The lower water absorption of the specimens with 5% and 10% GWD as PRC can be attributed to their denser and consequently less porous structure.

The results showed that the specimens with 5% and 10% GWD as PRC showed a lower water absorption of (9.5%, 9%) and (13.5%, 12%), respectively, after 7 and 28 days of curing when using TW and MW. In contrast with this result, as seen in Fig. 7 for both specimens produced with TW and MW, using higher amounts of GWD (>10%) leads to higher water absorption than that of the control specimens,. Therefore, the specimens with 20% GWD as PRC using TW and MW showed a higher water absorption of (4.5%, 4%) and (8.5%, 7%), respectively, after 7 and 28 days of curing relative to the controlled specimens.

The results also showed that, for all GWD incorporation ratios, the specimens with MW displayed a lower water absorption than that of the specimens produced with TW. This means that using MW to produce concrete specimens with GWD as PRC plays a positive role in decreasing the water absorption. The lower water absorption of the specimens with MW may be justified by the denser structure of the concrete matrix and consequently less porous structure. It was also found that the specimens with MW and 0%, 5%, 10%, 15% and 20% GWD as PRC displayed a lower water absorption by 12%, 9%, 12%, 13% and 9% after 28 days of curing relative to the specimens with TW.

3.4. Sulphuric acid resistance

The percentage variation in the mass of specimens produced with either TW or MW and GWD as PRC after exposure to a H_2SO_4 solution *versus* exposure time is displayed in Fig. 8. All specimens produced with either TW or MW and GWD as PRC displayed a better resistance to acid attack compared to the controlled specimens. This means that using of GWD as PRC could be an effective way to enhance the acid attack resistance of the concrete specimens regardless of the GWD incorporation ratio and the type of the water used to produce it. The specimens with 0% GWD as PRC produced with TW or MW showed a mass loss of 13% and 9%, respectively, after 70 days of exposure to a H_2SO_4 solution.

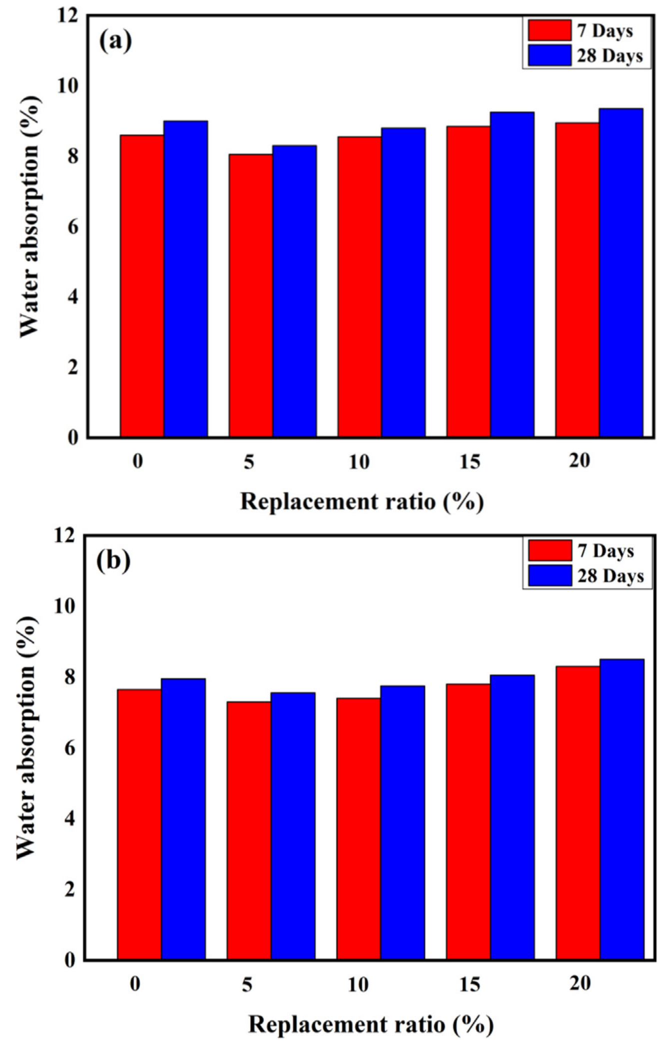

Fig. 7. Water absorption of concrete mixes with GWD as PRC using (a) tap water and (b) magnetized water after 7 and 28 days of curing in lime-saturated water.

As discussed before, the durability characteristics of concrete significantly depends on the porosity of its structure: a low porosity of concrete enhances its durability characteristics. The rate of the acid attack depends on several parameters, such as concrete's microstructure and pore structure, pH value and concentration of the sulphuric acid in the solution [47]. Therefore, the higher acid resistance of the specimens produced with either TW or MW and GWD as PRC regardless of the replacement ratio may be justified by the mxicrostructure improvement that results in a denser structure (less porous) of the matrix. The better acid resistance of the mixes with GWD may also be attributed to the greater acid resistance of the GWD particles compared to the cement particles.

As indicated in Fig. 8, for specimens produced with TW or MW, the maximum loss of mass was seen after 70 days of exposure to the H_2SO_4 solution. Fig. 8 also shows that, for all the mixes with GWD, there is an inverse relationship between the mass loss of the specimens and GWD's incorporation ratio, regardless of the water type used to produce the mixes. In other words, the mass loss of the specimens declines gradually as higher amounts of GWD are used to produce them. Therefore, the specimens with 20% GWD displayed the lowest mass loss reduction of all specimens when using either TW or MW.

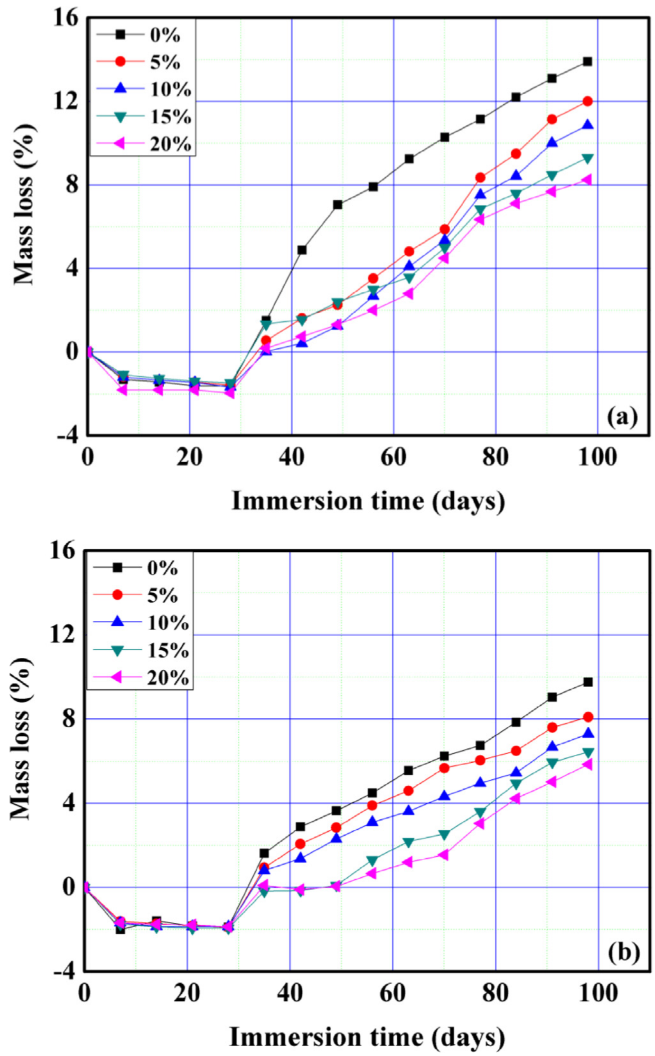

Fig. 8. Change in mass of concrete mixes with GWD as PRC using (a) tap water and (b) magnetized water exposed to a 5% by weight H_2SO_4 solution with pH 1.0 *versus* immersion time.

As seen in Fig. 8, all specimens with MW displayed a lower mass loss and consequently a higher resistance to acid attack than the ones with TW, regardless of the GWD incorporation ratio, at all testing days. As mentioned before, using MW to produce concrete leads to a denser structure and consequently to a lower number of pores and porosity.

Therefore, the higher acid attack resistance of the specimens with MW may be related to the less porous and enhanced microstructure of the concrete matrix. The results showed that the specimens with MW and 0%, 5%, 10%, 15% and 20% GWD as PRC displayed a lower mass loss by 31%, 32%, 33.5%, 30% and 29%, respectively, after 70 days of exposure to a H_2SO_4 solution relative to the specimens with TW.

3.5. Open circuit potential measurements

Fig. 9 shows the OCP measurements of steel rebars embedded in different concrete mixes exposed to 5% NaCl and H_2SO_4 solutions.

Generally, these measurements follow an increasing trend when curing in water for 28 days, due to the passive layer formation on the surface of the steel rebar. As the specimens are submerged in lime-saturated water for curing, the pH on the steel rebar's surface increases and reaches values around 12.5–13.5. Based on the Pourbaix diagram of the Fe-H_2O system, at this range of pH, the steel rebar is protected by an iron hydroxide layer formed on its surface [48].

During the curing period of the specimens, water is absorbed by the capillary action through the interconnected pores of the concrete structure and consequently can reach the steel rebar surface. Therefore, it is expected that, by increasing the content of GWD in the mixes, the water absorbed by the concrete matrix that can reach the steel rebar surface decreases due to the pore-filing action of GWD. This can be seen during the first days of curing in the mixes produced with TW (Fig. 9a and c). For the concrete mixes with 10%, 15% and 20% of GWD, the potential started at values between −400 and −300 mV, while for the controlled and 5% GWD mixes the measured potential shows values between −100 and −200 mV.

This may be attributed to the faster microstructure development of the concrete mixes with lower content of GWD as PRC due to their higher reaction rates as result of using higher contents of cement compared to the other mixes. For the mixes produced with MW, less difference can be seen between the potential of the controlled specimens and specimens with GWD during the first days of curing. As discussed previously, MW is more reactive than TW, which leads to higher interactions between the water molecules and cement particles. Because of this action, less water reaches the steel rebar's surface, which is enough to induce pH-increasing reactions and affect the recorded potentials. After 28 days of curing, the potential for all concrete mixes regardless of the water type is the same (around almost −100 mV).

Exposing the concrete mixes to 5% NaCl and H_2SO_4 solutions leads to a very different behaviour of the potential trend. The potential of the mixes exposed to the NaCl solution declines instantaneously while the overall potential remained constant or increased when exposed to the H_2SO_4 solution. Halide anions like chloride are believed to have a depassivator activity on the passive layer [49]. When a sufficient amount of chloride diffuses into the concrete matrix and reaches the steel rebar surface, a localized breakdown of the passive layer happens. This results in the dissolution of the bare steel, which leads to a drop of the measured potential.

On the contrary, in the H_2SO_4 solution, there is no ion that can induce direct depassivation. H_2SO_4 is dissociated into the proton (H +) and sulfate (SO_4^{2-}) in the water-based solution. To understand the effect of H_2SO_4 on the corrosion of reinforced concrete elements, the role of each ion must be clarified:

- SO_4^{2-}: A controversy can be found in the literature about the influence of the sulphate ion on reinforced concrete. Sulphate is reported to attack and deteriorate the concrete structure, while it has no significant effect on the corrosion of the steel rebar itself [50]. It is also stated that it can even inhibit the chloride attack on the steel rebar surface. On the contrary, there are studies which show the sulphate ion increases the corrosion rate of the steel rebars, but there is at least an agreement that the corrosive activity of sulphate is less than that of chloride ions when it comes to corrosion of the reinforced concrete structures [51];
- H^+: The diffusion of H^+ ion into the concrete matrix makes the environment more acidic. The passive layer on the steel rebar surface will be deteriorated if the pH there reaches thermodynamically unfavourable values for the passive layer's maintenance. Concrete itself, mainly due to presence of hydroxyl ions in the pore solution, has the ability to resist the protons, a phenomena that is known as neutralization capability [52]. As the proton diffuses to the pore solution, it reacts with the hydroxyl anions as follows:

$$Ca^{2+} + 2OH^- + 2H^+ \rightarrow 2H_2O + Ca^{2+}$$

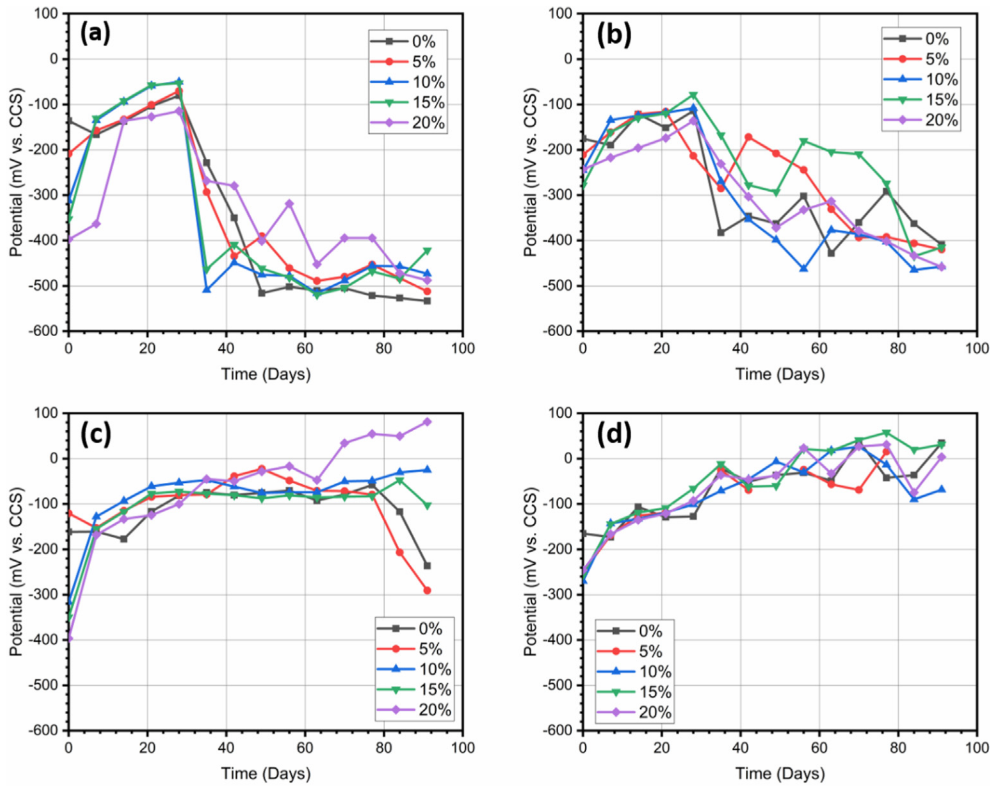

Fig. 9. OCP results of concrete mixes with GWD as PRC exposed to (a) 5% NaCl solution – tap water, (b) 5% NaCl solution – magnetized water, (c) 5% H_2SO_4 solution – tap water and (d) 5% H_2SO_4 solution – magnetized water. The potentials are relative to a copper copper-sulphate reference electrode according to ASTM C876-91. The concrete specimens were first cured in lime-saturated water for 28 days and then exposed to the NaCl and H_2SO_4 solutions for a period of 70 days.

which results in the neutralization and also transfer of the calcium ion to the solid phase and hence deterioration of the concrete matrix. Two main factors affect the acid attack of concrete: first, the diffusion ability of the acid through the concrete matrix to reach the reaction front and, second, the reaction rate or the neutralization capacity of the undamaged concrete [53].

Although the presence of GWD cannot change the neutralization capacity, its presence could help to slow down the diffusion of the acid through concrete. As shown in the mass loss results, the mix with 20% GWD shows the highest resistance to acid attack. As seen in the OCP results for mixes with TW (Fig. 9c), the mix with 20% GWD shows the highest values of OCP. Especially, after 70 days of exposure to the H_2SO_4 solution, Fig. 9c shows a significant decrease of the OCP values for the control and the 5% GWD mixes. For the mixes with MWD, the OCP values mostly increased until the final day of measurement (Fig. 9d). This can be due to the greater ability of MW to produce hydroxyls ions compared to TW, which leads to a greater neutralization capacity.

4. Conclusion

In this study, the simultaneous effect of GWD as PRC (up to 20%) and MW on the mechanical and durability characteristics of concrete exposed to two aggressive environments (5% by weight of NaCl and H_2SO_4 solutions) was investigated. To achieve the goals of this study, a number of tests such as compressive strength, resistance to acid attack, water absorption, and open circuit potential (OCP), were performed and the following conclusions were drawn:

- The results show that using GWD up to 10% as PRC improved the compressive strength of the concrete specimens regardless of the water type used to produce them during the curing process in lime-saturated water and after exposure to aggressive solutions (H_2SO_4 and NaCl) relative to the controlled specimens due to a less porous and denser cement matrix;

- Using higher amounts of GWD (>10%) decreased the compressive strength of the concrete specimens due to the lower cement content, regardless of the water type;

- MW improved the compressive strength of the concrete specimens relative to those produced with TW, regardless of the GWD incorporation ratio at all curing conditions;

- The compressive strength results revealed that an acid attack deteriorates the concrete structure while a chloride attack is not aggressive and does not decrease the compressive strength of the concrete specimens in short time, regardless of the GWD incorporation ratio and water type;

- Using GWD as PRC had a positive effect on the acid attack resistance of concrete, regardless of water type. Specimens with 20% GWD produced with either TW or MW displayed the highest resistance acid attack of all mixes;

- The mass loss results also indicated that the specimens produced with MW displayed a higher resistance to acid attack than that of the specimens produced with TW, which was attributed to a denser structure and consequently a lower number of pores and porosity;

- Specimens with MW displayed a lower water absorption than that of the ones with TW at all testing days, regardless of the GWD incorporation ratio. Using GWD up to 10% led to lower water absorption of the specimens compared to the control specimens, regardless of the water type used to produce them.

CRediT authorship contribution statement

Saeid Ghorbani: Methodology, Investigation, Formal analysis, Writing -Original draft, Visualisation and Writing -Review &

Editing. **Sahar Ghorbani:** Methodology, Investigation, Formal analysis, Writing -Original draft. **Amir Elmi:** Investigation. **Vala Soleimani:** Investigation. **Iman Taji:** Methodology, Investigation, Formal analysis, Writing -Original draft preparation. **Mohammad Mohammadi-Khatami:** Investigation. **Mohmmadreza Tavakkolizadeh:** Methodology, Review & Editing. **Jorge de Brito:** Conceptualisation, Methodology and Review & Editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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