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Improving corrosion resistance of steel rebars in concrete with marble and granite waste dust as partial cement replacement

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HIGHLIGHTS

- Marble and granite dust (MGD) incorporation did not significantly decrease concrete strength.
- Replacing cement by an adequate MGD content improved corrosion resistance.
- Using 20% MGD as cement replacement showed higher values of OCP and EIS.
- Water absorption should not be the only parameter for corrosion assessment in reinforced concrete.

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ABSTRACT

In this research, the effect of marble and granite waste dust (MGWD) as partial cement replacement (up to 20%) on the mechanical and corrosion behaviour of concrete specimens was investigated. Water cured specimens were kept in a 3.5% by weight of NaCl solution for 92 days. Uniaxial compression and water absorption tests, open circuit potential (OCP), electrochemical impedance spectroscopy (EIS) and Scanning Electron Microscopy (SEM) analysis were conducted. The compressive strength test results showed insignificant negative effect from using MGWD. OCP and EIS measurements revealed that specimens with 20% cement replacement have higher potentials and corrosion resistance than all the others.

1. Introduction

In recent years, the production of waste materials has increased due to the growth of industrial activities around the world. The high consumption of natural resources has led to greater environmental degradation. On the other hand, most of these waste materials have negative effects on the environment. Concrete is the most widely used construction material around the world [1]. Therefore, recycling and reusing these industrial wastes in concrete production could be considered an effective way to reduce the environmental impacts of these polluting materials. In addition, using these waste materials in concrete production has the potential to make significant environmental and economic contributions.

In past decades, a variety of waste materials, such as marble and granite waste dust (MGWD), tire rubbers, metallic based furnace slag, silica fume, fly ash and lime stone, have been widely used in concrete production [2–7]. Previous researches have shown that using these waste materials in concrete production can improve its properties, namely its compressive strength, workability and durability [3–8]. MGWDs is considered a by-product obtained during marble and granite boulders processing, which includes shaping, sawing, cutting and polishing for different applications. The marble and granite industry generates large amounts of MGWD during the production process, specifically the cutting process of marble and granite rocks. The produced waste dust could be used in different applications, for instance as filler, cement replacement or modifying materials in concrete production [2,9–34]. Ergün's [18]

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investigation showed that using 5.0% and 7.5% of waste marble dust as partial cement replacement leads to an increase in compressive strength. Shirule et al. [19] reported that the compressive and splitting tensile strength of concrete specimens increases with the use of waste marble dust up to 10% as partial cement replacement. Aliabdo et al. [20] studied the effect of marble waste dust as partial cement or sand replacement at 5%, 7.5%, 10% and 15% by mass. The test results showed that using marble waste dust as partial cement or sand replacement improves the mechanical properties of concrete, mainly due to a filler effect. Demirel [21] reported that the reduction of porosity was associated with the filler effect of marble dust on cement hydration. Khodabakhshian et al. [22] also reported that the strength and durability of concrete containing waste marble dust as partial cement replacement tend to decline for replacement ratios over 10% but satisfactory results were obtained below that level of replacement. According to Abukersh and Fairfield [23], using granite dust as partial cement replacement at 20–50% significantly reduces the compressive strength of concrete specimens while the effect on the tensile strength is negligible. It was also reported that using granite sludge as partial cement replacement (up to 7.5%) increases the durability of concrete mixes without affecting their strength and workability [24]. Arivumangai and Felixkala [25] also reported that using 25% granite dust as addition has a positive effect on the strength and durability of concrete mixes.

Since the production of cement, the primary component of concrete, is one of the main causes of air pollution due namely to CO_2 emissions, the use of MGWD as partial replacement of cement has the potential to significantly reduce these emissions as a result of lower cement production. Previous researches have been shown that replacing 10% of cement used in concrete production with marble dust would reduce the CO_2 emissions by 12% [18,35]. According to the data collected in 2014, replacing 10% of cement with marble dust would reduce the world CO_2 emissions from 3.95 to 3.55 billion tones [1]. Therefore, using MGWD as replacement of cement could introduce a new technology and material that reduces the use of cement in concrete production.

There is an important durability problems in reinforced concrete (RC) members and structures, the corrosion of steel rebars embedded in them, which can reduce their service life due to the penetration of harmful chemicals and ions into a highly permeable concrete matrix, as shown by previous researches [36]. In fact, damage due to the corrosion of steel rebars has been identified as the primary cause of significant number of structural failures over the past century [37]. This phenomenon can be particularly serious in environments with chloride penetration and carbonation risks. Steel rebars embedded in concrete are normally in a passive state due to the high alkalinity of the pore solution of concrete, which provides an ideal environment that can protect the steel rebars from corrosion. The alkalinity mainly depends on the type of the cement used in concrete production. However, alkalinity is important but is not the only aspect governing reinforcement corrosion initiation and (later on) serious corrosion development [38]. In addition the corrosion process of steel rebar embedded in concrete also depends on the electrochemical potential of the steel and the existence of voids at the interface between steel rebar and concrete, as well as the presence of aggressive ions such as chloride and sulphate [36,39].

As there is a lack of information on the effect of MGWD, as partial replacement of cement, on the corrosion behaviour of RC members, the aim of this research is to evaluate the influence of these two waste materials on the mechanical and corrosion behaviour of reinforcement concrete. Different proportion of MGWD were used as cement replacement in order to produce several concrete mixes and, after preparation of RC specimens, the corrosion performance of the steel rebars was evaluated for 92 days of exposure to a 3.5% NaCl solution using potential measurements as well as impedance spectroscopy.

2. Experimental program

2.1. Materials

Concrete in this study is produced under controlled conditions at room temperature using Portland cement, water, fine and coarse aggregates. The cement used was manufactured by Zaveh Cement Company complying with the Type II Portland cement requirements, as stated in ASTM C150. The chemical composition of cement is presented in Table 1. The coarse aggregate used is crushed limestone and the fine aggregate is river sand acquired locally.

The range of the coarse and fine aggregate is mostly between 0.3–10 mm and 5–20 mm, respectively. The particle size distributions of both the fine and coarse aggregate are shown in Fig. 1. MGWD was obtained from a local marble and granite processing factory. The granite and marble slurry were first completely dried in an oven to produce dust before replacing part of the cement, in order to control the water/binder ratio. The specific gravity of the marble and granite waste dust used in this study is 2.50 and 2.61, respectively. The chemical composition of MGWD and its particle size distribution are given in Table 1 and shown in Fig. 2,

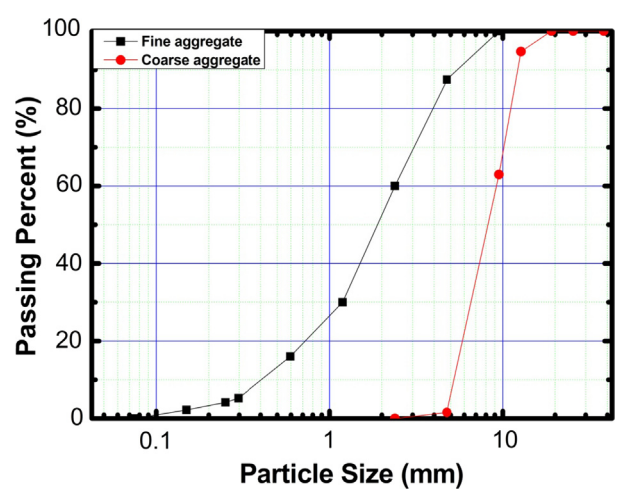

Fig. 1. Particle size distribution of fine and coarse aggregates.

Table 1
Chemical composition of the granite and marble dusts.

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
Marble	1.3	85.3	0.6	0.4	0.6	0.3	0.1	0.1	0.02	2.4

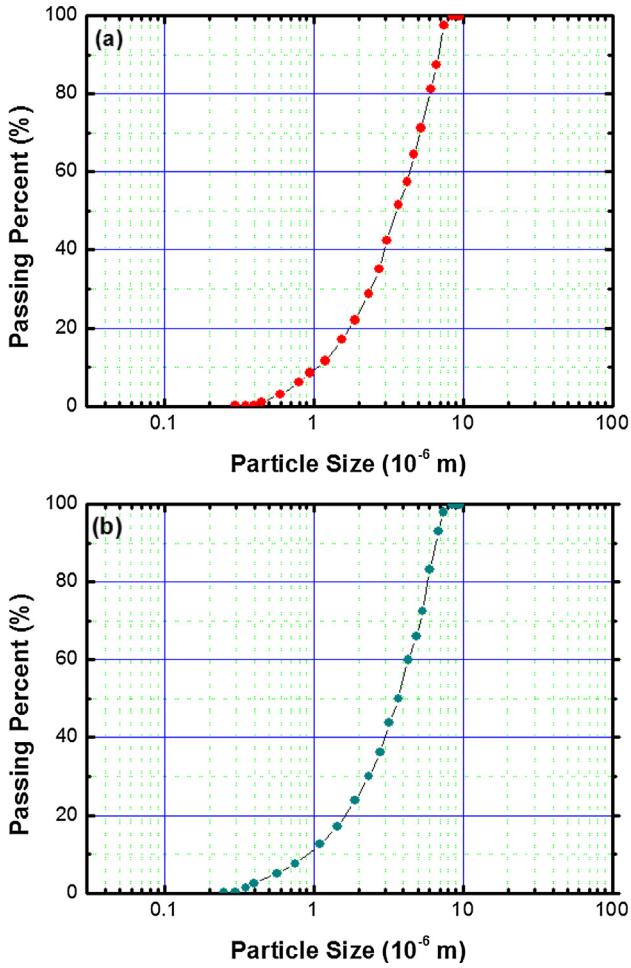

Fig. 2. Particle size distribution: (a) marble dust and (b) granite dust.

respectively. The chemical analyses and particle size distribution of MGWD were carried out using XRD and laser size grading, respectively. The mixing water was regular tap water from the laboratory. The steel reinforcement was structural steel rebar with 16 mm diameter (A615).

2.2. Mix composition

The experimental program is divided in two parts. The first part covered the effect of MGWD as replacement of cement on the compressive strength and water absorption of concrete mixes. The second part addressed the corrosion behaviour of RC specimens similarly modified with MGWD. The main factors considered were the cement/MGWD replacement ratio as well as the exposure time to a 3.5% NaCl solution. The cement replacement ratios were 0%, 5%, 10%, 20% and (by mass) with granite dust, marble dust or as combination of the two, while the binder content of all mixes was 400 kg/m^3. The w/c ratio of all mixes was 0.5. The composition of the various mixes is seen in Table 2.

2.3. Testing

2.3.1. Compressive strength

In order to determine the compressive strength of the concrete mixes, cylindrical moulds with 150 mm diameter and 300 mm height were used, according to ASTM C39. The specimens were cast in plastic moulds, demoulded after 24 h and cured by immersing in lime saturated water and then kept at room temperature. The specimens were tested after 7 and 28 days from the casting date. A load-controlled hydraulic jack with a capacity of 3 MN was used. The average compressive strength of at least 3 specimens was reported as the compressive strength of each mix.

2.3.2. Corrosion resistance

In order to determine the corrosion resistance of reinforced concrete, cylindrical moulds with 100 mm diameter and 200 mm height were prepared and a 200 mm long steel rebar with 16 mm diameter placed in the centre of the specimen. The experimental setup of the corrosion tests is schematically shown in Fig. 3. The specimens were cast and then demoulded after 24 h. The specimens were cured by submerging in saturated lime water for 27 more days at room temperature. After 28 days, in order to determine the corrosion resistance of RC specimens exposed to an aggressive environment, they were immersed in a NaCl solution (3.5% by weight). The chloride solutions were prepared by adding sodium chloride (NaCl) in a sufficient amount of deionized water, as it is the most commonly encountered source of chlorides. The open circuit potential (OCP) was measured for 120 days using a saturated calomel electrode (SCE) as reference. Electrochemical impedance spectroscopy (EIS) was also used to determine the corrosion resistance behaviour of rebars in concrete, using a Zive Lab Potentiostat device. EIS is a powerful technique to characterize a wide variety of electrochemical systems and detect small corrosion occurrences in the metallic parts [40]. It is also the most common technique to evaluate and study corrosion in reinforced concrete [40–42]. A conventional three electrode setup was used. A rebar segment was employed as a working electrode. A platinum wire and a SCE were used as counter and reference electrode, respectively. All potentials in this study are referred to SCE. The EIS test was repeated 3 times for each testing day in order to insure reproducibility.

Table 2
Composition of the concrete mixes.

Mix No.	Composition (kg/m^3)							
	Granite (%)	Marble (%)	Cement	Granite	Marble	Water	Fine*	Coarse**
1	0	0	400	0	0	200	714	1000
2	5	5	360	20	20	200	699	995
3	0	10	360	0	40	200	699	995
4	10	0	360	40	0	200	699	995
5	10	10	320	40	40	200	685	989
6	0	20	320	0	80	200	685	989
7	20	0	320	80	0	200	685	989

* Fine aggregates.
** Coarse aggregates.

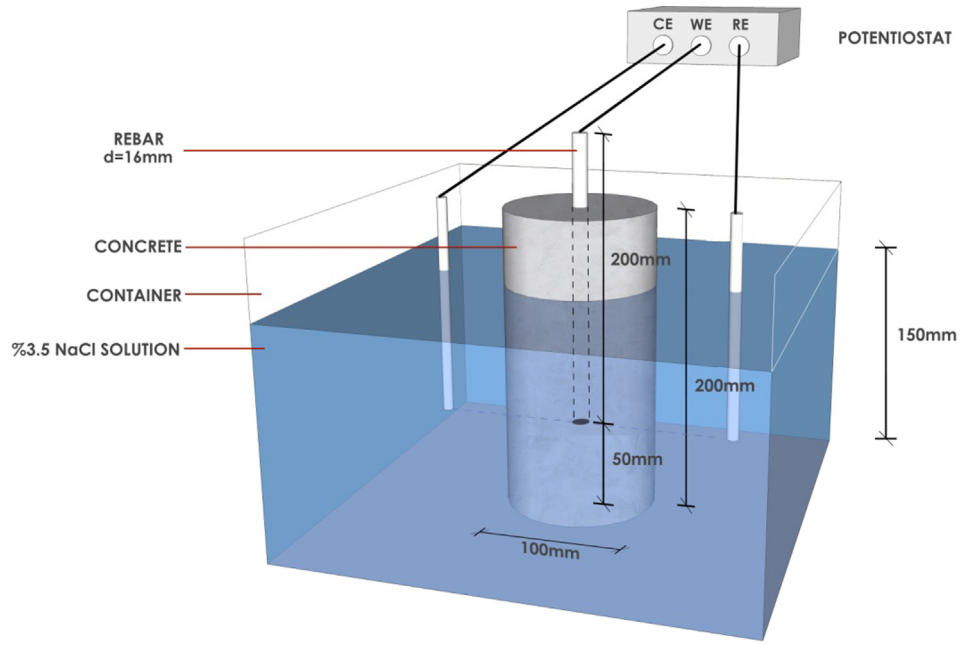

Fig. 3. Experimental setup of the corrosion tests.

2.3.3. Water absorption

Absorption is usually measured by drying a specimen to a constant mass, then immersing it in water and measuring the saturated surface dry mass, according to ASTM C642. The ratio of the difference between two measured masses and the dry mass is named water absorption. It was reported as the average value of three cylindrical specimens tested after 28 days of curing.

3. Results and discussion

3.1. Compressive strength

Fig. 4 shows the compressive strength of the concrete mixes modified with MGWD as partial cement replacement after 7 and 28 days of curing in saturated lime water. Each point of the plot is an average value of three independent readings for specimens from one batch. Using MGWD as partial cement replacement did not significantly affect the compressive strength of the mixes after 7 and 28 days of curing. Fig. 4 also shows that concrete specimens with 10% waste dust as partial cement replacement had a higher compressive strength that of the control specimens. This result is in good agreement with previous studies [20,22,26,43], which reported an improvement in compressive strength of concrete specimens by using 5–15% marble dust [20,22,26] and 10% granite dust [26,43] as cement replacement, respectively. The use of 10% granite dust as cement replacement displayed the most positive effect and increased the compressive strength about 1.14 and 1.09 times after 7 and 28 days, respectively, compared to the control specimens. This higher compressive strength of specimens may be due to the pore filling effect of very fine MGWD that enhances the density of the interfacial transition zone products. The largest decrease in compressive strength of the specimens after 28 days was 0.94 and 0.96 times for concrete mixes with 20% granite and marble dust, respectively. This means that the compressive strength of concrete mixes with MGWD decreases with excessive content of MGWD as cement replacement due to the reduction of cement content and adhesion of the cement paste, as reported previously [26]. The specimens with 20% granite waste dust as cement replacement displayed the worse results and had a compressive strength lower by about 0.89 and 0.94 times after 7 and 28 days, respectively, compared to the control specimens. Nevertheless, it should be noted that the changes in compressive strength of the various mixes after 28 days were not significant and can be considered almost negligible. Finally, Fig. 4 shows that, as curing continued, the compressive strength of all concrete mixes increased but the rate of increase varied as reported in previous researches [44]. Also, as the curing age increased, the compressive strength loss decreased.

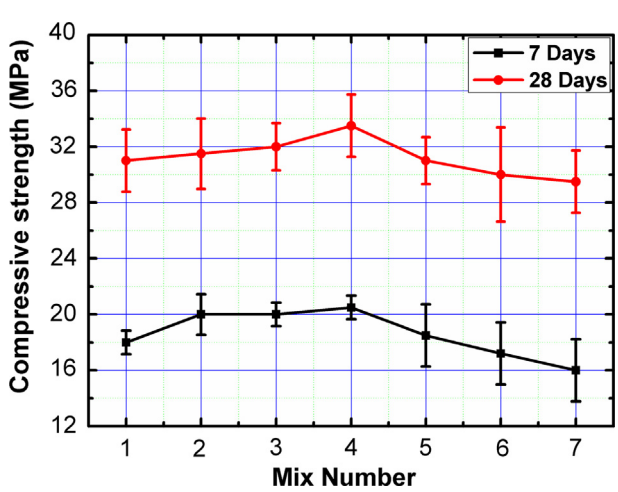

Fig. 4. Compressive strength of the mixes with MGWD *versus* time of exposure. The error bars are represented with a confidence level of 90%.

3.2. Corrosion properties

3.2.1. Open circuit potential measurements

Measuring OCP or half-cell potential is one of the common methods to evaluate the corrosion state of steel rebars in RC members. Due to the simplicity of this method, it is generally used in industrial and laboratory applications. However, it should be noted that the potential cannot show the exact state of corrosion because

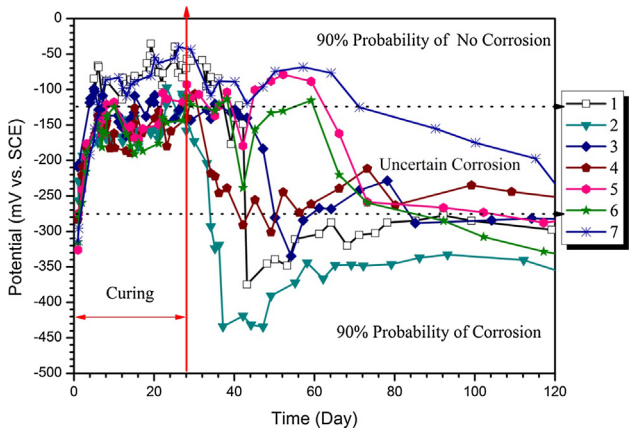

Fig. 5. Open circuit potential of all mixes after 28 days of curing and 92 days immersion in 3.5% NaCl. Dotted lines show the areas of corrosion probability according to ASTM C876-91.

the process of corrosion is related to the transfer of current or flow of electrons via the anodic dissolution of metal (M) with the reaction of $M \rightarrow M^{n+} + n\bar{e}$. This is illustrated in ASTM C876-91, which introduces a standard test method for half-cell potentials of uncoated reinforcing steel in concrete. According to this standard, a half-cell potential should not be interpreted as an indicator of corrosion rate, or even as an indicator of a corrosion reaction. However, the corrosion potential could be a suitable estimation of the corrosion state of the rebar in concrete and it could show the probability of corrosion. According to ASTM C876-91, there are three OCP ranges for the estimation of corrosion:

a) 90% probability of no corrosion for OCP >− 126 mV/SCE;
b) Uncertainty of corrosion for −126 < OCP >− 276 mV/SCE;
c) 90% probability of corrosion for OCP <−276 mV/SCE.

The variation of average OCP values of the steel rebars embedded in concrete over 120 days of immersion (28 days in lime saturated water and 92 days in a 3.5% by weight NaCl solution) is presented in Fig. 5. Each point of the curves represents the average value of three independent measurements. Fig. 5 shows that the potentials increased positively during the water curing period. In fact, during the water curing period, the pH level of the steel–concrete interface increases and usually reaches the value of 12 [45]. The rise of the pH level leads to the formation of a passive layer on the steel rebar surface. This layer is responsible for decreasing the corrosion rate and increasing the open circuit potential. After the specimens are placed in a NaCl solution, chloride ions can penetrate thorough the concrete pores and reach the steel rebars

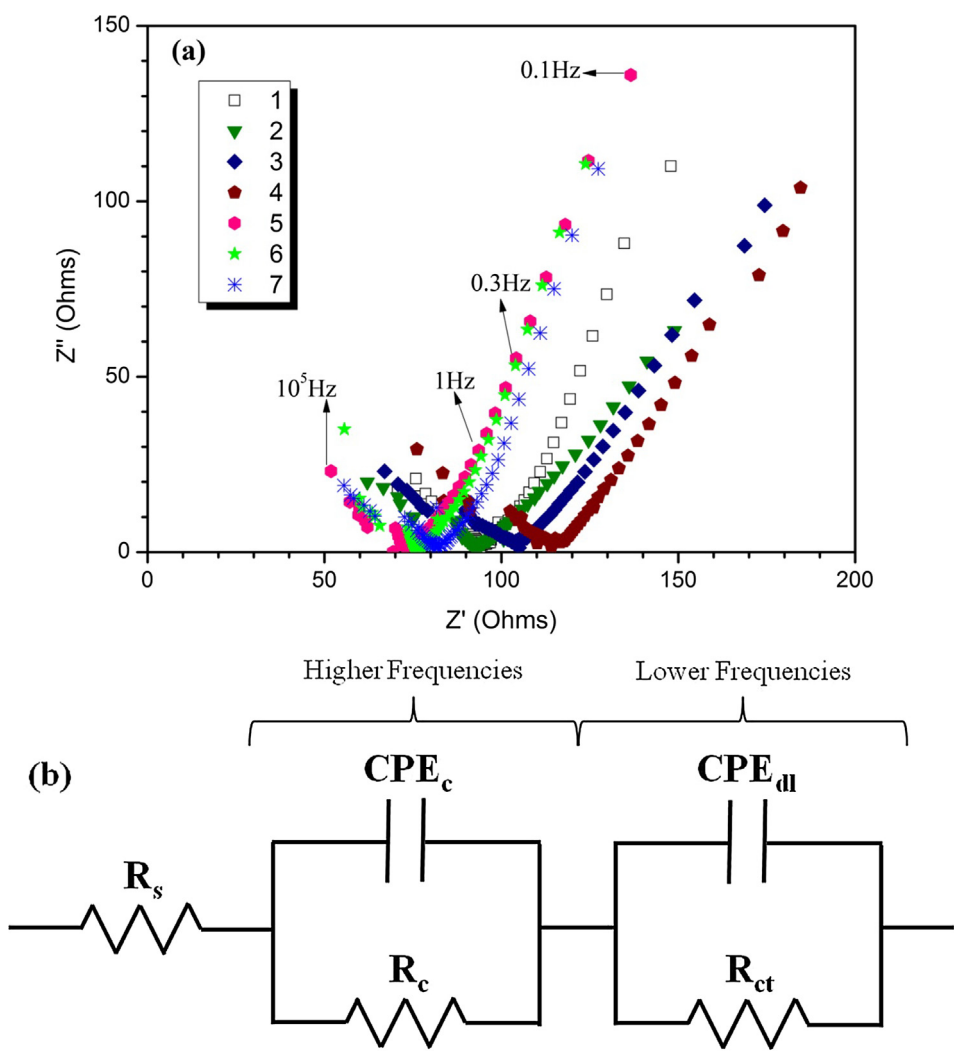

Fig. 6. EIS measurement test, (a) Nyquist diagram of the mixes after 14 days of immersion in 3.5% NaCl, (b) the equivalent circuit used to fit the EIS data of rebars.

surface, deteriorating the passive layer. Due to the depassivation of steel rebars as a result of chloride attack, the corrosion potential falls. As seen in Fig. 5, after 28 days of water curing, all the mixes fall in the range of 90% probability of no corrosion or near it. As the specimens are exposed to the NaCl solution, the OCP declines, but the decrease rate is not the same for all specimens. The OCP value of mixes 1 and 2 after approximately 6 and 15 exposure days to the solution, respectively, entered the corrosion range and remain in it for the duration of the experiment. However, after a while the OCP value of mixes 3 and 4 reached the corrosion range threshold and fluctuated around the border of uncertain corrosion and 90% probability of corrosion for the 120 days of exposure. The best corrosion behaviour was displayed by mix 7 that did not enter the corrosion range during the 120 days of exposure. However, the slope of its potential curve demonstrated that it might move into the corrosion range after a longer period. The OCP value of mixes 5 and 6 did not enter the corrosion potential range until nearly 74 and 58 days of exposure to the solution, respectively. It can be concluded that using MGWD as cement replacement improved the potential behaviour of steel rebars. Indeed, the higher amounts of dust led to higher potentials. Mixes with 20% waste dust as cement replacement (5, 6 and 7) showed higher potential values.

3.2.2. Electrochemical impedance spectroscopy

The impedance of steel rebars embedded in concrete was measured at 14, 28 and 90 days after immersion in a 3.5% NaCl solution. The results of EIS as a Nyquist plots for 14th day of immersion are represented in Fig. 6. EIS measurements were performed on three independent specimens from each mix and a representative curve was reported. As illustrated in Fig. 6, all the mixes showed two capacitive characteristics (i.e. two semi loops). The high frequency tail of the Nyquist plot corresponds to the concrete that covers the steel rebar. The lower frequency part of the diagram is related to the metal surface. So the conventional equivalent circuit for concrete as shown in Fig. 6-b was used to model the EIS data. This circuit contains a parallel resistance (R_c) and capacitance (CPE_c) for coated concrete at higher frequencies in series with a parallel charge transfer resistance (R_{ct}) and double layer capacitance (CPE_{dl}) of the metal surface in lower frequencies. A constant phase element was used as a replacement of capacitor element in this study. Indeed, in electrochemical systems the metal surface was not believed to act as a perfect capacitor, so a constant phase element is defined to model the double layer. Imperfection of capacitance characteristics in electrochemical systems is originated from the inhomogeneity of the metal surface. The *CPE* consists of two elements: *P* which refers to CPE magnitude and *n*, a parameter which explains the deviation of the semicircles from an ideal capacitive behaviour. The *n* value changed between 0 and 1. If it equals 1, that shows that the surface acts as an ideal capacitor. In other words, it can be said that the higher the value of *n*, the more smoothness of the steel surface is expected. In Fig. 6-b a solution resistance also appeared in series with other above-mentioned elements. The value of the solution resistance was related to the resistivity of the 3.5% NaCl solution, which is very low and negligible, compared to the resistance of other elements. As seen in Fig. 6, the surface response of the metal had larger loop in comparison with the concrete related part, so it is expected that the corrosion characteristics of the system is controlled by the metal surface elements (i.e. R_{ct} and CPE_{dl}).

As illustrated in Fig. 7, mixes 5, 6 and 7 showed larger loops than others, while mixes 2, 3 and 4 had the smaller loops. In order to quantitatively compare the EIS data, the results were analysed using an EIS analyser software and fitted with the aforementioned equivalent circuit, and are presented in Table 3. The data concerning EIS experiments after 14, 28 and 90 days were reported in this table. The variations of R_{ct}, P_{dl} and n_{dl} as a function of time for all

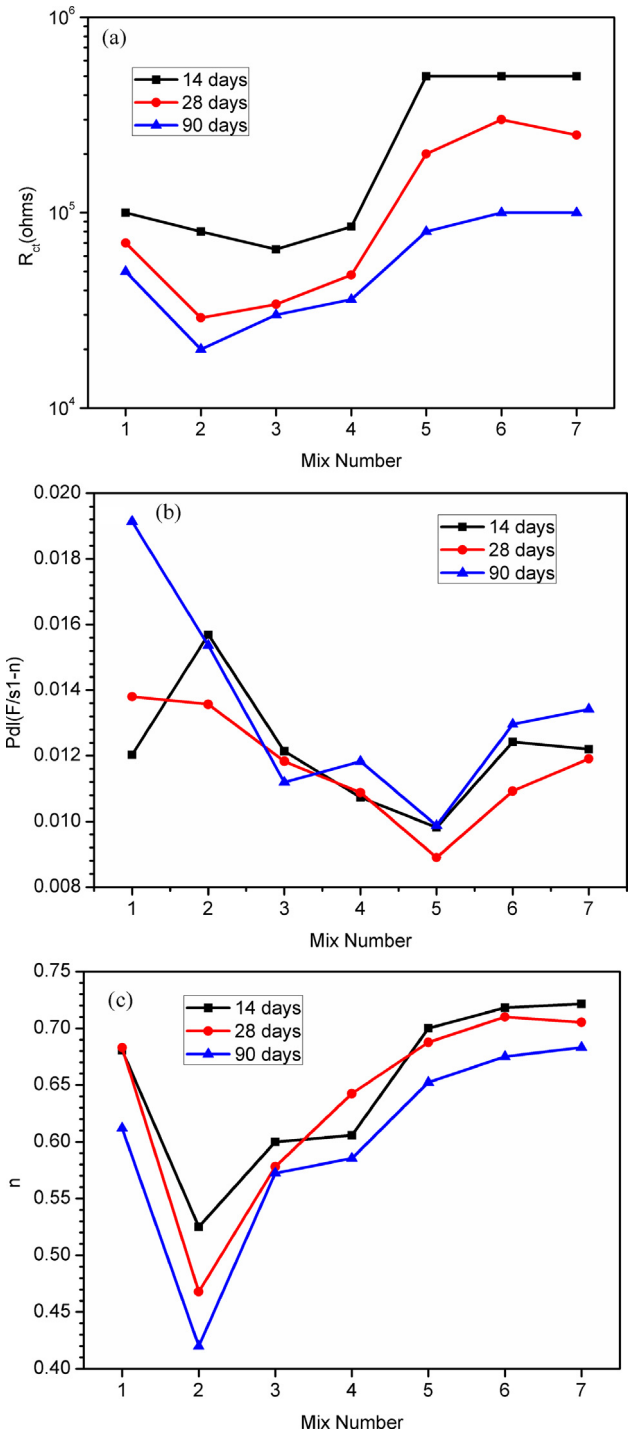

Fig. 7. Fitted data of EIS measurements of all mixes after 14, 28 and 90 days of immersion in 3.5% NaCl, (a) R_{ct} represents the charge transfer resistance, (b) P_{dl} reveals the magnitude of constant phase element of double layer and (c) *n* shows the deviation of *CPE* from ideal behaviour.

mixes are shown in Fig. 6. Fig. 6-a shows that, generally, the value of R_{ct} decreases as time increases. In addition, it is clear that the value of R_{ct} for mixes 2, 3 and 4 was lower compared to that of the control mix, while in mixes 5, 6 and 7 the value of R_{ct} the opposite occurred after 14, 28 and 90 days of immersion. It is concluded that increasing the ratio of MGWD as cement replacement (here 20%) can enhance the corrosion properties of RC members. This higher corrosion resistance of steel rebars may be attributed to the improved microstructure of concrete matrix due to the

Table 3
EIS test parameters of the mixes obtained by fitting with EIS analyser software.

Mix No.	Testing day	R_s (Ω)	R_c (Ω)	P_c (F/s^{1-n})	n_c	R_{ct} (Ω)	P_{dl} (F/s^{1-n})	n_{dl}
1	7	4	90	4.70×10^{-07}	0.68	1×10^5	0.012	0.68
	14	5	95	1.30×10^{-06}	0.6	7×10^4	0.014	0.68
	90	6	80	9.90×10^{-05}	0.28	5×10^4	0.019	0.61
2	7	7	89	4.16×10^{-06}	0.5	8×10^4	0.015	0.52
	14	6	110	5.29×10^{-06}	0.47	2.9×10^4	0.013	0.47
	90	4	90	1.79×10^{-06}	0.59	2×10^4	0.15	0.42
3	7	5	97	2.46×10^{-06}	0.6	6.5×10^4	0.012	0.6
	14	5	110	2.71×10^{-05}	0.39	3.4×10^4	0.012	0.58
	90	6	115	7.75×10^{-05}	0.34	3.0×10^4	0.011	0.57
4	7	4	110	3.66×10^{-06}	0.52	8.5×10^4	0.010	0.6
	14	4	108	3.61×10^{-05}	0.35	4.8×10^4	0.011	0.64
	90	6	105	1.6×10^{-04}	0.26	3.6×10^4	0.012	0.58
5	7	5	68	1.0×10^{-06}	0.66	5.0×10^5	0.010	0.7
	14	3	68	9.7×10^{-07}	0.64	2.0×10^5	0.009	0.68
	90	6	70	1.43×10^{-06}	0.61	8.0×10^4	0.010	0.65
6	7	4	71	1.6×10^{-06}	0.65	5.0×10^5	0.012	0.72
	14	5	68	4.62×10^{-07}	0.69	3.0×10^5	0.011	0.71
	90	5	66	8.11×10^{-06}	0.49	1.0×10^5	0.013	0.67
7	7	6	75	1.06×10^{-05}	0.47	5.0×10^5	0.012	0.72
	14	5	79	2.48×10^{-05}	0.43	2.5×10^5	0.012	0.7
	90	4	80	2.04×10^{-05}	0.44	1.0×10^5	0.013	0.65

micro-filler action and enhanced bonding capability of the MGWD particles. This may have reduced the porosity, pore diameters and air content and increased the internal surface area of the cement matrix. Consequently, the permeability of the concrete matrix decreases. This is likely to be the major reason for the corrosion improvement of the mixtures since the particle size distributions of the MGWD are finer than that of the Portland cement. Consequently, the chloride diffusion coefficient and thus the rate of corrosion fall. On the other hand, the lower ratio of MGWD as cement replacement resulted in a decrease in corrosion resistance of rebars, as reported in previous researches [2]. It can also be claimed that the higher corrosion resistance of the steel rebars may be due to the use of calcareous materials such as marble dust. Using it as partial cement replacement may increase the surface alkalinity of the steel rebar embedded in concrete and even help long-term corrosion resistance, as reported in previous researches [38]. In addition, it was reported that the porosity of concrete mixes with 7.5%, 10.0% and 15.0% granite dust as cement replacement increases [2]. This may be confirmed by n_c data presented in Table 3, showing the greater values of mixes 5 and 6 relative to mixes 1, 2, 3 and 4. Indeed, the higher the n_c value, the more homogeneity and less porosity of the concrete mixture are expected. Even though some fluctuations can be observed in the P_{dl} results (Fig. 7-b), the overall trend showed that using MGWD as cement replacement decreased the P_{dl} value. So adding MGWD in some mixes could improve the corrosion resistance (i.e. increase R and decrease P) of the steel rebar surface in comparison with the control mix Regarding the value of n, in Fig. 7-c, it is obvious that, as the exposure time to the NaCl solution increases, the n values decrease, which is related to the increase in surface roughness due to the corrosion of the steel and formation of corrosion products. Furthermore, from the EIS data, it can be concluded that there was no significant difference resulting from MGWD as cement replacement.

3.3. Water absorption

The water absorption of the control mix and of the concrete mixes with MGWD as cement replacement after 28 days of water curing is shown in Fig. 8. Each point of the plot is an average value of three independent measurements. As seen in Fig. 8, MGWD had no significant effect on the water absorption of all specimens, which varied between 5.5% and 7.0%. So it can be assumed that

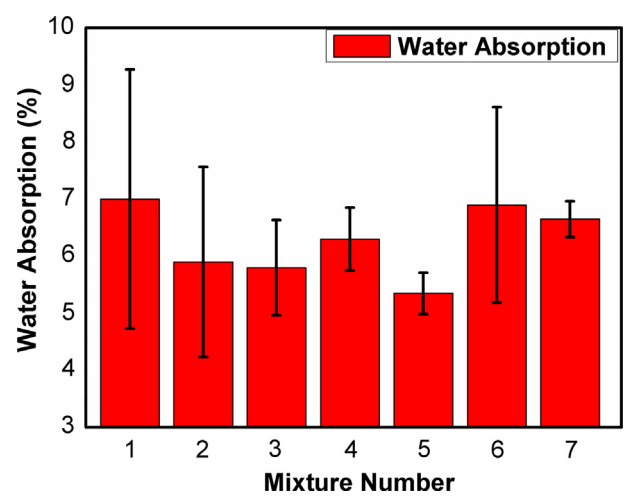

Fig. 8. Water absorption of the mixes with granite and marble dust. The error bars are represented with a confidence level of 90%.

using 10% and 20% of MGWD as cement replacement did not significantly change the water absorption of concrete. Therefore, it may be concluded that the water absorption was not directly associated to the corrosion performance of steel rebars embedded in concrete. It should be noticed that three diffusion-related factors have great influence on the corrosion initiation and propagation in steel rebars embedded in concrete:

a) Water diffusion to the steel rebars/concrete interface;
b) Oxygen diffusion through concrete towards the steel rebars surface;
c) Chloride penetration to the steel rebars surface.

The first factor is essential to provide an electrolyte media for more feasible ion exchangeability at the steel rebar surface. The second one is necessary for cathodic half-cell reaction and the third one accelerates the anodic reaction of iron and deteriorates the formed passive layer. When a corrosion layer is not formed on the steel rebar's surface, oxygen is the only depolarization agent for the cathode of the steel corrosion process in concrete via the following reaction: $2H_2O + O_2 + 4e \rightarrow 4OH^-$ [36]. So, the cathodic

reaction in concrete depends on the control of oxygen diffusion. Due to the molecular diameter, the permeation rate of water is greater than that of oxygen and chloride. The diffusion rate of these three molecules rank as follows: $H_2O > O_2 > Cl^-$ [46]. In agreement with previous researches [47], it seems that, despite the necessity of water at the early stages of corrosion, the permeability and absorption properties of the concrete do not play a key role on the corrosion performance of reinforced concrete. Indeed, it is more relevant to consider the oxygen and chloride diffusions for cathodic and anodic reactions, respectively.

3.4. Scanning electron microscope analysis

After 92 days of immersion in a 3.5% NaCl solution, steel rebars were separated from the surrounding concrete. Regarding corrosion, visual inspection revealed that the surface of all steel rebars remained intact. Only some small local corrosion products were observed (confirmed by SEM) in specimens 1 and 2 through 4 (10% replacement) close to the rib edges of the steel rebars. Gerengi et al. also reported that most of the corrosion products occurred between the spiral ribs of the steel rebars [48]. Fig. 9 schematically shows the typical locations of the corrosion products. Fig. 10 displayed a typical surface of a steel rebar after being exposed to the NaCl solution after 92 days using SEM imaging. Apparently, visual inspection and SEM images agree. Fig. 11-a through -c showed typical corroded areas at the edges of the ribs in mixes 1 (control specimen), 4 (10% replacement) and 7

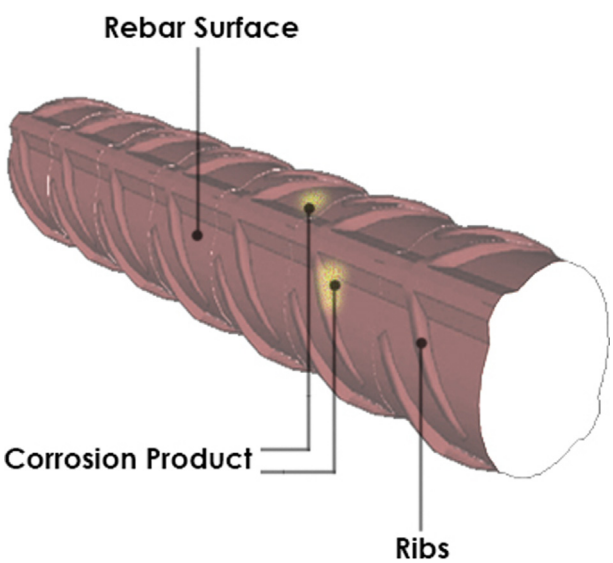

Fig. 9. Typical locations at which the corrosion products appeared.

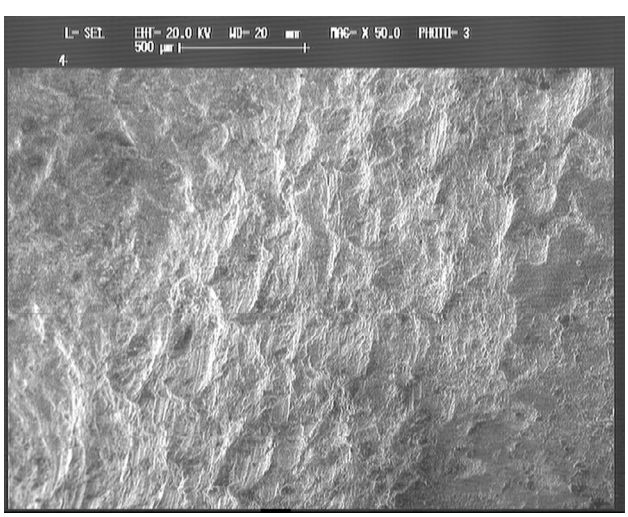

Fig. 10. Typical surface of a steel rebar after exposure to a NaCl solution for 92 days using SEM image.

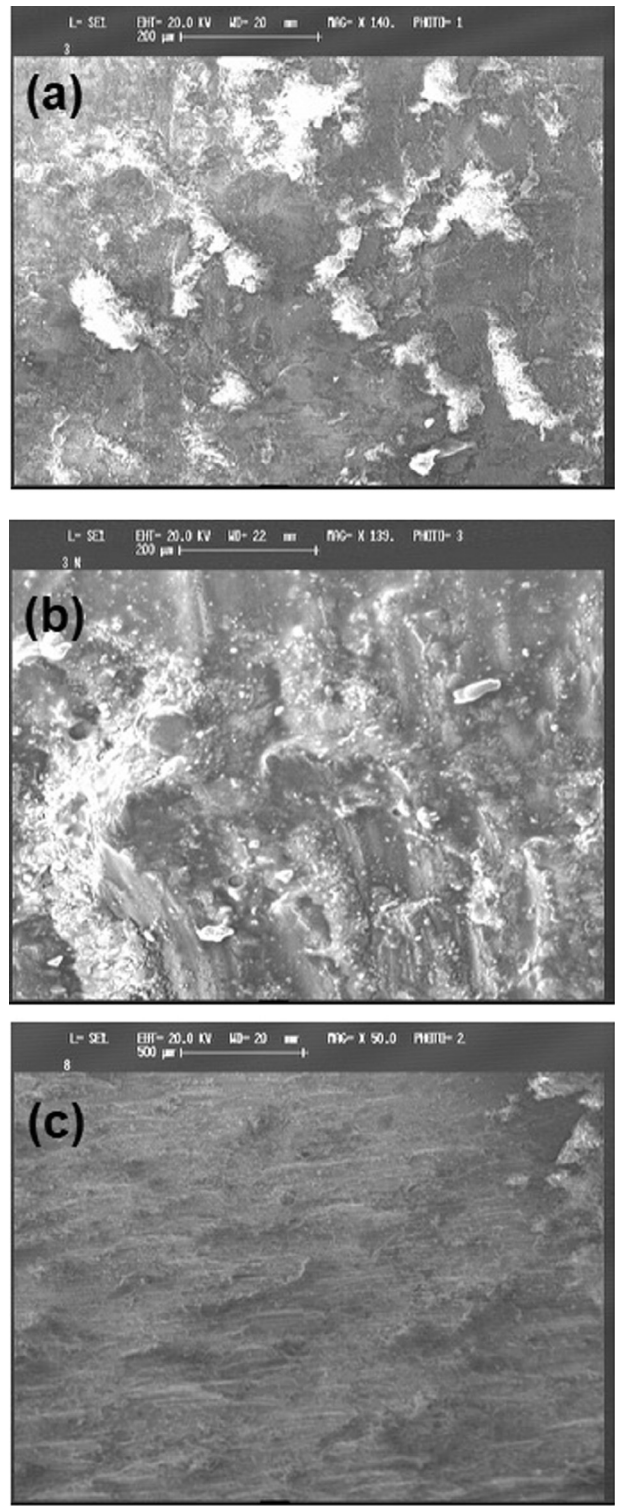

Fig. 11. SEM images of corrosion products on rebars within (a) mix 1, (b) mix 4 and (c), mix 7 (clean surface of steel).

(20% replacement), respectively. The amount of corrosion products on rebars embedded in mix 1 was apparently significantly higher than that in mix 4, in which the corroded areas detected on the steel rebars were not severe. Additionally, the steel rebars in embedded in mix 7 displayed almost no sign of corrosion products even at the rebar edges. Generally, there was no sign of pitting corrosion on the steel rebars and the corroded areas detected were not severe. Therefore, based on the observation of SEM and previous sections, in this study, a suitably corrosion resistant concrete mix with 20% cement replacement (by either marble, granite or their combination) was presented.

4. Conclusions

In this research, the effect of marble and granite waste dust (MGWD) as partial cement replacement on the corrosion behaviour and mechanical properties of RC members has been investigated and the following conclusions were drawn:

- Using MGWD as cement replacement did not significantly effect the compressive strength of concrete. The highest decrease in 28-day compressive strength of specimens was 5% by using 20% granite dust by mass;
- OCP measurements showed that mixes with 20% MGWD as cement replacement generally corresponded to higher corrosion potentials (i.e. less probability of active corrosion) than those with lower waste contents;
- EIS measurement showed that cement/MGWD replacement at 10% and 20% displayed little deterioration and significant improvement in corrosion resistance, respectively;
- The *n* values showed that the surface of steel rebars in mixes with 10% cement replacement were rougher than those with 20% cement replacement after 92 days of exposure to a 3.5% NaCl solution;
- The compressive strength and water absorption of mixes with MGWD as cement replacement up to 20% by mass did not significantly change. Therefore, these two parameters by themselves, especially water absorption, should not be considered as reliable parameters for the assessment of corrosion potential in concrete;
- After 92 days exposure to a 3.5% NaCl solution, no corrosion product was observed on the steel rebars surface using SEM image analysis except a few localized rebar regions in mixes with 0–10% cement replacement.

Conflict of interest

The authors have no conflict of interest whatsoever.

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