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Influence of Saline-treated Wastewater on Properties of Concrete: An Experimental Study

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Abstract

The rapidly growing world population and the accompanying increase in concrete production to meet building and infrastructure needs have led to significant increase in potable water consumption, which resulted in several environmental problems. This paper investigates the feasibility of replacing potable water with highly mineralized treated wastewater in concrete mixing in order to make concrete production more eco-friendly in an arid region. Concrete specimens were prepared using saline treated wastewater (saline-TWW) as mixing water and compared to those mixed with distilled water (DW) and with the performance requirements given by the mixing water quality standards. The results revealed that the concrete mixes produced using saline-TWW exhibited higher early strength and a similar long-term strength than the control mix produced using DW. It was also found that the use of saline-TWW increased the setting times of cement paste but had no remarkable effect on the workability of fresh concrete mixture. Furthermore, the microstructural characteristics of the hardened concrete were assessed by water-permeability test, SEM image analysis, and X-ray diffraction tests. The results revealed that saline-TWW concrete exhibited a more compact microstructure and smaller pore sizes than their counterparts of DW, which means an improvement in the durability of saline-TWW concrete. Moreover, an electrochemical test was conducted to estimate the extent of corrosion of the steel embedded in reinforced mortar specimens prepared using saline-TWW and DW. The electrochemical test results showed that the use of 100% saline-TWW as mixing water of concrete resulted in a high corrosion rate of the embedded steel.

Keywords

concrete, saline-TWW, mixing water, strength, chloride, corrosion

1 Introduction

The fresh and hardened properties of concrete make it an excellent choice for construction projects [1]. As a result, concrete production exceeds all other engineering materials combined, reaching more than 16 billion metric tons per year [2]. However, the high consumption of energy, materials and water associated with this enormous concrete manufacturing has resulted in diverse local, regional, and global environmental problems. As a result, extensive research projects have been conducted recently to adverse the durability and sustainability of concrete by using different industrial waste and by-products to replace, partially or totally, Portland cement and natural aggregates in ordinary concrete. These include silica fume [3], fly ash [4], metakaolin [5], recycled aggregates [6], etc. However, less attention is given to lowering water consumption in concrete production.

Water is an essential ingredient of concrete: it is necessary for mixing and curing concrete and also is used for washing aggregate and concrete machinery and equipment after use [7]. The concrete industry consumes about 16.6 billion cubic meters of water annually, a volume equivalent to approximately 18% of annual global industrial water consumption [8]. This water demand can cause additional management complications for water resources in regions where water scarcity is already a problem or will become a problem in the next future. Therefore, developing measures to reduce the concrete industry's water consumption should be considered as a high priority to make concrete production more eco-friendly. It is reported that the best strategy for reducing water consumption in the production of concrete is the reduction of mixing water [8] because potable water is commonly recommended for use as its

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chemical composition is constantly tested and well regulated. Therefore, there are many sources of water unsuitable for drinking, such as river water, seawater, domestic and industrial wastewater, and grey water of ready-mixed concrete plants, which may, in certain situations, be suitable as concrete mixing water [9].

There have been numerous experimental investigations on concrete produced using seawater with no remarkable adverse effects reported on the strength of concrete, either in the long or short term [10, 11]. However, mixing reinforced concrete with seawater is currently interdicted because the high chloride content in seawater catalyzes the corrosion of the reinforcing steel. Many other studies were also conducted on concrete produced by different industrial wastewater sources, including car washes, textile industry, heavy industry, and palm oil mills [12]. Wash water from concrete batching plants and mixer trucks has also been evaluated for use as mixing water with no significant effects reported on fresh concrete properties, mechanical properties, corrosion, and resistance to sulfate attack [13–14]. The reported results showed that the fine solids content of wash waters affect positively the durability of concrete by reducing the porosity and water absorption of concrete [14]. On the contrary, it has been reported that the use of wash waters containing more than 50 000 ppm total solids in concrete mixtures leads to a reduction in concrete's resistance to acid attack and the effectiveness of admixtures [15]. Furthermore, treated domestic wastewater has been tested for mixing and curing concrete. Tay and Yip [16] have found that treated domestic wastewater used partially or totally as mixing or curing water had no adverse influence on concrete's setting time and compressive strength. Al-Gussain and Terro [17] found that concrete mixed with tertiary-TWW was identical to that produced using tap water, not only in the fresh properties and compressive strength but also in durability and corrosion potential of steel. However, they found that concrete made with preliminary and secondary-TWW showed lower strength and more effect on retarding setting times. These results can be related to the difference in dissolved organic substances between preliminary, secondary, and tertiary-TWW. As well, the amount of chemical oxygen demand (COD) in the primary-TWW used by Ghrair and Al-Mashaqbeh [18] as mixing water resulted in 30 min increase in the initial setting time of PPC cement and a significant decrease in the long-term compressive strength of concrete. Asadollahfardi et al. [19] also found that the COD concentrations in the TWW before chlorination caused a decrease of 6% in the 28-day compressive strength of concrete and an increase in the setting times of OPC cement. Meena and Luhar [20] remarked an improved abrasion resistance and a reduced ability to resist to the penetration of chloride ions and carbonation when they used tertiary-TWW as mixing and curing water. Hassani et al. [21] reported that the high amount of COD of TWW results in higher chloride ions penetration depth, especially in higher water/cement ratio. Peighambarzadeh et al. [22] found that mixing and curing concrete by TWW contains a low amount of COD had no marked effect on the fracture toughness of concrete.

From the above literature review, it can be said that the effect of impure mixing water on the physical and mechanical properties of concrete depends on its origin, especially its chemical constituents. However, many studies are still needed to improve the requisite information for the safe application of various types of impure water in concrete mixing [7], especially in the water-stressed regions of the world. For example, there appear to be no detailed studies on the influence of highly mineralized treated wastewater on various properties of plain and reinforced concrete. Therefore, the objective of this experimental study is to investigate the applicability of using saline-TWW obtained from the Saïd-Otba wastewater treatment plant in Ouargla province for concrete mixing. Ouargla is situated in the southern arid regions of Algeria, where freshwater supply is provided only by brackish groundwater. Therefore, the valorization of saline-TWW as mixing water for concrete in this arid region could reduce the consumption of potable water, which is in most cases desalinated water, and decrease environmental impacts and concrete production costs.

2 Experimental program

2.1 Materials and mixture proportions of concrete

Two types of mixing water were used in this study: saline treated wastewater (saline-TWW) and distilled water (DW). A sulfate resisting cement CEMI 42.5N conforming to EN 197-1 [23] was used for concrete producing. The oxide compositions of the cement are listed in Table 1. As fine aggregate, locally available river sand having a fineness modulus of 2.48 and density 2.61 g/cm^3 was used. As a coarse aggregate, crushed limestone gravel having a density of 2.62 g/cm^3 was employed in three sizes. Fig. 1 shows the grain-size distributions of the aggregates employed in this study. The maximum chloride content of the fine and coarse aggregates was 0.003% and 0.005%, respectively.

Table 1 Chemical composition of sulfate resisting cement

Composition	Amount (wt %)
SiO_2	16.74
Al_2O_3	4.02
Fe_2O_3	2.88
CaO	63.35
K_2O	0.54
MgO	1.68
Na_2O	0.07
SO_3	2.16
Cl	0.02
C_3S	63.61
C_3A	5.78
C_4AF	12.23
Insoluble residual	0.81
Loss on ignition	0.81

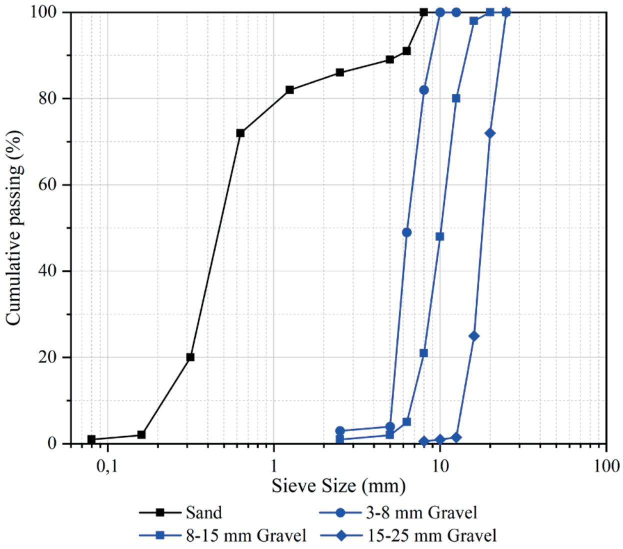


Fig. 1 Particle size distribution of the aggregates

In this study, a total of four concrete mixes with variable percentage of saline-TWW were investigated. The reference concrete mixture (DW) was designed by using the method of Faury [24] to achieve 75±10 mm slump and 25 MPa 28-day compressive strength. After that, the distilled water (DW) was replaced by saline treated wastewater (saline-TWW) in the content of 25, 50, and 100%. The replacement percentage is equal to the weight of saline-TWW/total weight of DW in the concrete mix. The mix proportions of the investigated concrete mixtures are shown in Table 2.

2.2 Preparation of concrete and reinforced mortar test specimens

Concrete cylinders (Ø15 cm × H30 cm) were cast under similar conditions using the four concrete mixes to investigate the compressive strength after various curing times. The test specimens were prepared according to EN 12390-2 [25]. The concrete was mixed using pan type mixer and compacted using a vibrating table. After 24 h of casting, the concrete specimens were demolded and cured in a humid chamber at 95% humidity and 23°C until the respective test ages.

The reinforced mortar specimens for electrochemical measurements were made as per EN 480-14 [26] in the form of cylinders (Ø45mm x H113mm) centrally reinforced with a steel bar of 6 mm in diameter (Fig. 2). The cylinders were cast using standard mortars prepared with DW and saline-TWW as mixing waters. Before being used, the steel specimens were polished using SiC abrasive papers (from P60 to P240 grit) to remove the oxide scale and then coated with epoxy as shown in Fig. 2, leaving an exposure length of 70 mm corresponding to 13.47 cm^2 of exposed area. After demolding, reinforced mortar specimens were placed in the humid chamber for 120 days.

2.3 Test methods

2.3.1 Mixing water quality

For the purpose of this study, saline treated wastewater samples collected from the sedimentation pond of the Saïd-Otba wastewater treatment plant were subjected to chemical analysis in accordance with the standard methods [27]. The chemical analysis results of TWW were then compared to the compositional requirements specified by EN 1008:2002 [28] and ASMT C1602 [29] standards.

Table 2 Mixture proportion of concretes (kg/m^3)

Mix Type	Cement	Sand	Coarse aggregate			Mixing water	
			3–8 mm	8–15 mm	15–25 mm	DW	Saline-TWW
DW	350	630	265	375	495	210	-
Saline-TWW25						157.5	52.5
Saline-TWW50						105	105
Saline-TWW100						-	210

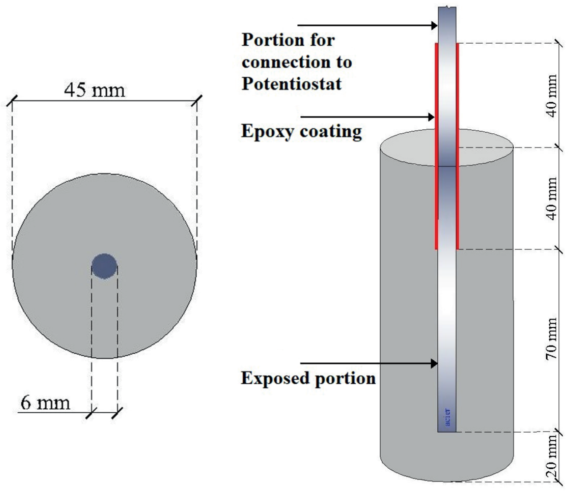


Fig. 2 Schematic representation of the reinforced mortar specimen

2.3.2 Setting times

The setting times of cement pastes produced using different percentages of saline-TWW were conducted according to EN 196-3 [30]. The test results were then compared to the requirements of EN 1008:2002 [28] and ASMT C1602 [29] standards on setting times of cement paste. These standards specify that the time of setting of cement paste mixed with questionable water supplies should not be more than 1 hour earlier or 1 hour 30 min later and not differ by more than 25% from the control time of setting obtained with cement paste mixed with potable or distilled water.

2.3.3 Workability and Compressive strength of concrete

The workability of the fresh concrete mixtures was evaluated by the slump-cone test in accordance with EN 12350-2 standard [31].

The compressive strength of concrete was determined according to EN 12390-3 standard [32]. The 7-day compressive strength results obtained using different percentages of saline-TWW were compared to the requirements of EN 1008:2002 [28] and ASMT C1602 [29] standards on concrete's compressive strength. These standards specify that the 7-day compressive strength of concrete specimens mixed with the questionable water supply must be at least 90% of the compressive strength of the specimens prepared with potable or distilled water.

2.3.4 Permeability and microstructure of hardened concrete

To estimate the durability performance of hardened concrete, water permeability measurement was performed according to EN 12390-8 standard [33]. The test was performed in half of 15 × 30 cm^2 concrete cylinders after 180 days. The test measures the depth of water penetration under constant pressure (500 ± 50 kPa) for 72 hours through the top face of the concrete specimens. The water penetration depth was determined after breaking the tested specimens into two halves.

X-ray diffraction on concrete powder samples was also performed to characterize the crystalline hydrate phase of concrete. The concrete powder was scanned from 10° to 60° (2θ) with a step of 0.02° 2θ. The microstructural characteristics of hardened concrete were also evaluated using scanning electron microscopy (SEM). Broken concrete specimens obtained after the compressive strength test at 12 months of curing were used for SEM analysis.

2.3.5 Electrochemical study

The electrochemical measurements were evaluated by a potentiodynamic polarization test (Tafel curves). As shown in Fig. 3, the test was performed using a saturated calomel reference electrode, a platinum counter electrode, a saturated $Ca(OH)_2$ solution as the electrolyte, and the steel specimen embedded in mortar as the working electrode. The three electrodes were connected to

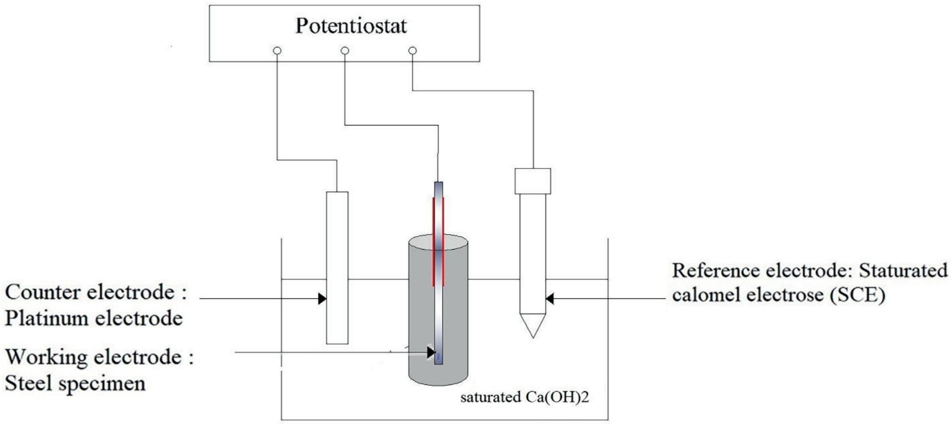


Fig. 3 Schematic of electrochemical polarization cell

a potentiostat (Voltalab PGZ-301), and the potential of the steel sample was polarized from to -900 mV to +900 mV at a sweep rate of 50 mV/min. The electrochemical parameters were calculated using Voltamaster 4 software. The average values of two replicate reinforced mortar specimens from each type of mixing water were reported.

3 Results and discussion

3.1 Mixing water quality

The presence of excessive amounts of organic and inorganic impurities in untried mixing water may not only affect the strength development of concrete and setting time of cement but also may cause other adverse effects in concrete, such as efflorescence, shrinkage, corrosion of reinforcement, and reduced durability [9]. For these reasons, the saline-TWW used in this study was first subjected to chemical analysis, and the test results are presented in Table 3.

It can be derived from the results presented in Table 3 that the TWW used in this study contains excessive amounts of chloride, sodium, and sulfate ions. It contains about five times more chloride ions than the tolerable limit for reinforced concrete specified by EN 1008:2002 [28] and ASMT C1602 [29] standards and contains about four times more sodium oxide than the tolerable limit specified by EN 1008:2002 standard. The concentration of sulfate ions in the tested effluent also exceeds the tolerable limits. However, the amounts of total solids, lead, zinc, and nitrate in the saline-TWW were within the acceptable limits specified by EN 1008:2002 and ASMT C1602 standards. In addition, the BOD and COD contents in the utilized TWW, which qualifies the organic pollutants in the water, were higher than the acceptable limits recommended by Mehrdadi et al. [34].

The high concentration of salts in the TWW used in this study can be attributed to the wastewater's initial quality; brackish groundwater is the only source of water supply for the inhabitants in the region of Ouargla. To reveal the effect of its salinity on various properties of concrete, the saline-TWW used in this study was compared with the seawater salinity used by Younis et al. [11], for example. As shown in Table 3, the difference between the saline-TWW used in this study and the seawater used by Younis et al. [11] is that the amount of sulfate in our study was larger; it was 33% higher than that in the seawater used by Younis et al. [11]. However, total solid content and chloride ions in the utilized TWW were less than in the sweater studied by Younis et al. [11].

3.2 Setting time and workability

Fig. 4 shows the results of the setting time test of cement pastes. It can be observed from the results indicated that the cement's setting times were increased when DW was replaced by saline-TWW. With the replacement of 25%, 50%, and 100% of DW by saline-TWW, the initial setting times of cement pastes were 07 min, 16 min, and 25 min longer, and the final setting times of cement pastes were 11 min, 21 min, and 45 min longer compared to those of the control cement paste, respectively. However, these results indicated that the use of saline-TWW meets the permissible limits of setting times given by EN 1008: 2002 [28] and ASMT C1602 [29] standards. The delay in setting time, which means the increase in time during which concrete can be transported, placed, and finished, obtained in this study, may be interesting in hot weather concreting applications. The obtained results of setting time in this study using saline-TWW are consistent with the results of Asadollahfardi et al. [19] and Abushanab and Alnahhal [35].

Table 3 Chemical characteristics of saline-TWW compared to the tolerable limits and seawater utilized by Younis et al. [11] (all values are in mg/l except pH)

Component	Saline-TWW utilized in this study	Seawater utilized by Younis et al. [11]	Tolerable limit
pH	7.33	8.2	≥ 4 [28]
Total solids	18 300	30 300	50 000 [29]
Chloride (Cl^-)	5 125	18 600	500-4 500 (depend on concrete type) [28, 29]
Sodium (Na^+)	4 023	-	1 500 As (Na_2O_{eq}) [28]
Potassium (K^+)	71	-	
Sulfate (SO_4^{-2})	3 148	2 359	3 000 [29]
Nitrate (NO_3^-)	0.023	-	≤ 100 [28]
Lead (Pb^{+2})	0.152	-	
Zinc (Zn^{+2})	0.053	-	
BOD_S	30	-	18 [34]
COD	114	-	70 [34]

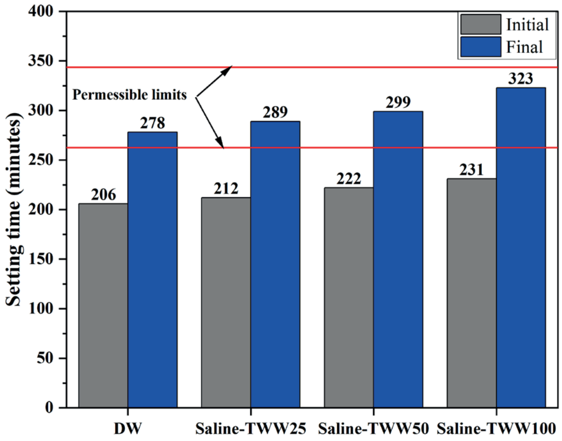


Fig. 4 Setting times of cement pastes

It could also be noticed from Fig. 4 that cement setting times increased with increasing the saline-TWW replacement percentage. This can be attributed to the concentration of organic compounds, which caused a delay in the hydration of C3S. It is reported that the presence of even small concentrations of certain organic compounds in the concrete mixture can lead to a significant influence on the setting time of cement [36]. Among them, propionate, triethanolamine, diethanolamine, glyoxal, and urea exhibit an acceleratory effect on the hydration reaction, whereas lignosulfonates (sugar), hydroxyl-carboxylic acids, and carbohydrates cause a retardation effect. The retardation effect may be ascribed to the adsorption of organic compounds of mixing water on the hydration products of C3S, such as CH and C-S-H [36].

The slump values of concretes were measured to assess the consistency of saline-TWW fresh concrete. It was found that the slump values for the four types of concrete mixes varied between 75 and 78 mm, indicating that the use of saline-TWW as a replacement of DW has no remarkable effect on the slump value of the fresh concrete. The results of Al-Gussain and Terro [17], Asadollahfardi et al. [19], and Abushanab and Alnahhal [35] also indicated that TWW has only a negligible effect on concrete workability.

3.3 Compressive strength

Results of the compressive strength tests are summarized in Table 4.

Table 4 Compressive strength of concretes mixed with Saline-TWW

Mix Type	Compressive strength (MPa)				
	7 days	28 days	90 days	180 days	365 days
DW	24.69	46.29	50.29	52.41	55.40
Saline-TWW25	25.04	45.80	49.15	51.14	53.12
Saline-TWW50	26.31	44.80	47.44	49.90	54.22
Saline-TWW100	32.35	43.26	49.46	51.98	56.60

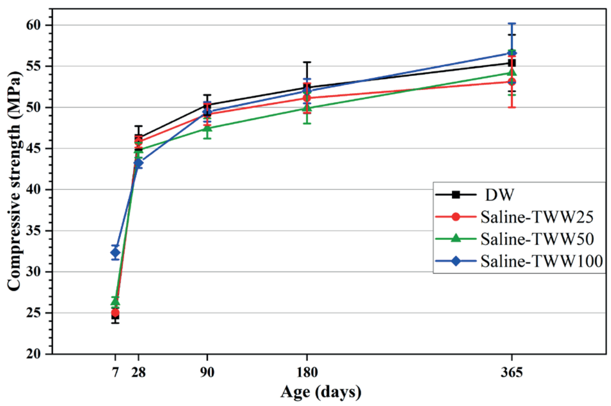


Fig. 5 Variation of compressive strength of concrete with curing ages

Each represented value is the average compressive strength of three cylindrical concrete specimens. Fig. 5 shows the graphical representation of the compressive strength development in concrete containing 0, 25, 50, and 100% saline-TWW. The results presented in Table 4 and Fig. 5 indicated that all concrete mixes prepared using saline-TWW exhibited higher early strength than the control mix prepared using DW. It could be observed that the concrete specimens produced using 25%, 50%, and 100% of saline-TWW had 1.4%, 6.5%, and 31% higher 7-day compressive strength, respectively than the control specimens prepared using DW, which meet the requirements specified by EN 1008: 2002 [28] and ASMT C1602 [29] standard. It could also be observed that increasing the percentage of saline-TWW lead to an improvement in the 7-day compressive strength of concrete. This can be related to the high concentration of chloride ions in saline-TWW, which lead to the acceleration of the C3S hydration [36]. Due to the rich chloride content, seawater was also reported to accelerate the compressive strength at early ages [37]. Furthermore, the 7-day compressive strength results indicate that the initial retardation of cement hydration did not impair the early strength development of saline-TWW concrete mixes. This can be explained by the fact that the amount of organic compounds was strongly reduced in the aqueous solution after a certain period of time by absorption on C-S-H and CH crystals.

After 28 days of mixing, all concrete mixes produced using saline-TWW had slightly lower compressive strengths than the control specimens. The results indicate that the 28-day compressive strengths of concrete specimens produced using 25%, 50%, and 100% saline-TWW were about 1%, 3.2%, and 6.5% lower than the compressive strength of the control specimens, respectively. Further, the concrete 28-day compressive strength gradually decreased by increasing the percentage of saline-TWW. This can be explained by the difference in ionic concentration between pore solutions and the outside of the specimens of saline-TWW, which caused the leaching of some hydration products of cement past and resulted in a loss of compressive strength. As a result, the total replacement of DW by saline-TWW reported the maximum reduction of the 28-day compressive strength, while the reduction was slighter for the partial replacement of DW. Similar observations were reported on the 28-day compressive strength of seawater concrete [11, 37]. Younis et al. [11] reported an increase in early compressive strength of seawater-mixed concrete followed by a reduction of 7–10% at 28 days age compared to the resistance of freshwater-mixed concrete.

For ages of three months and higher, as illustrated in Fig. 5, it can be noticed that the compressive strengths of concrete specimens prepared using various percentages of saline-TWW and those prepared with DW were similar. These results indicate that the long-term compressive strength of Portland cement concrete is independent of the chemical composition of the mixing water. This observation was supported by Mohammed et al. [38] in seawater-mixed concrete. The obtained results also showed that the leaching of cement past observed in saline-TWW concrete samples at 28 days was significantly decreased with the increase of the age of concrete.

3.4 Permeability and microstructure

The permeability is a perfect indicator of the quality and durability of concrete when subjected to an aggressive salt solution [39]. Table 5 presents the depth of water penetration on hardened concrete of all mixes. The water permeability coefficients (K_p) were calculated using Eq. (1) [40].

$$K_p = \frac{d^2}{2ht}, \tag{1}$$

where d = depth of water penetration (m); t = pressure time (s) and h = water hydrostatic head (m).

It can be deduced from the results of Table 5 that all saline-TWW concrete mixes were less permeable than the DW concrete mix. The lower permeability of saline-TWW concrete mixes may be attributed to the pore size distribution of hydrated concrete. Generally, the pores inside concrete are mainly classified as micropores (<5 nm), mesopores (5–50 nm), and macropores (>50 nm). It is reported that macropores are more responsible for determining the concrete strength and impermeability characteristics, whereas micropores and mesopores are more influential in drying shrinkage and creep [39]. In view of the above, it can be concluded that saline-TWW concrete mixes exhibited lower amounts of macropores and higher amounts of micropores and mesopores compared to those formed in DW concrete. Similar observations were reported by Shi et al. [37] on the refined pore structure of seawater concrete. This can be ascribed to the effect of chloride ions on the acceleration of C3S hydration, which results in the formation of a less dense C-S-H with a high surface area and a larger amount of fine pores than in the control concrete [36]. This can be confirmed by comparing the SEM images of the fractured surfaces of the concrete samples shown in Figs. 6 and 7, which indicated that saline-TWW100 concrete exhibited a more compact microstructure and smaller pore sizes than their counterparts of DW.

Table 5 Results of the water permeability of saline-TWW concretes

Mix Type	Depth of water penetration (mm)	Water permeability coefficient (m/s)
DW	25	2.36×10^{-11}
Saline-TWW25	21	1.66×10^{-11}
Saline-TWW50	22	1.83×10^{-11}
Saline-TWW100	18	1.23×10^{-11}

Fig. 8(a) shows the XRD results of DW and saline-TWW100 concrete mixes at 12 months of age. XRD results indicate the presence of dolomite (D), quartz (Q), Portlandite (P), and calcium carbonate (CCB) peaks. The quartz and dolomite are derived from the concrete aggregates. As shown in Fig. 8(b), the XRD patterns indicate low-intensity peaks of Friedel's salt observed in the saline-TWW100 concrete. The calcium chloroaluminate, known as Friedel's salt, may be formed through the reaction of C_3A and C_4AF phases and chloride from the mixing water as in Eq. (2) [41].

$$\begin{aligned} &C_3A + 2NaCl + Ca(OH)_2 + 10H_2O \rightarrow \\ &C_3A + CaCl_2 + 10H_2O + 2Na^+ + 2OH^-. \end{aligned} \tag{2}$$

As seen from Eq. (2), Friedel's salt is an important compound for the chemical binding of internal chloride ions. It is reported that C_3A content of the cement is the most important factor governing the chemical binding capacity of chloride [36]. As the lower C_3A content of the SRPC cement used in this study, the intensity of Friendl's salt peak is lower due to the lower amount of Friedel's salt formed.

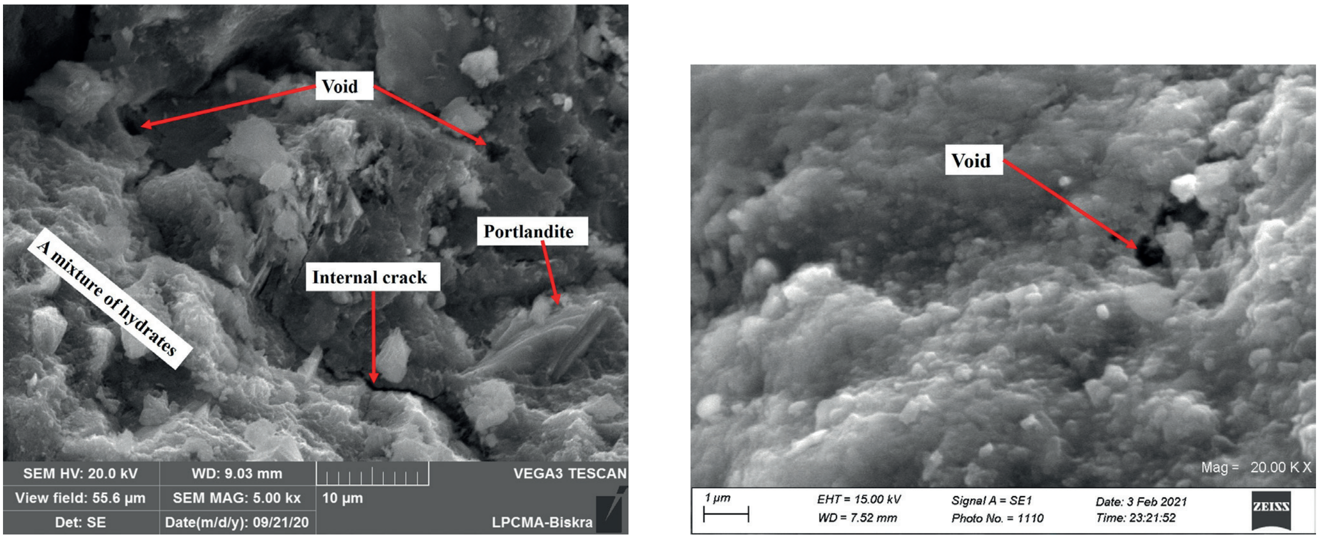


Fig. 6 SEM images of DW concrete

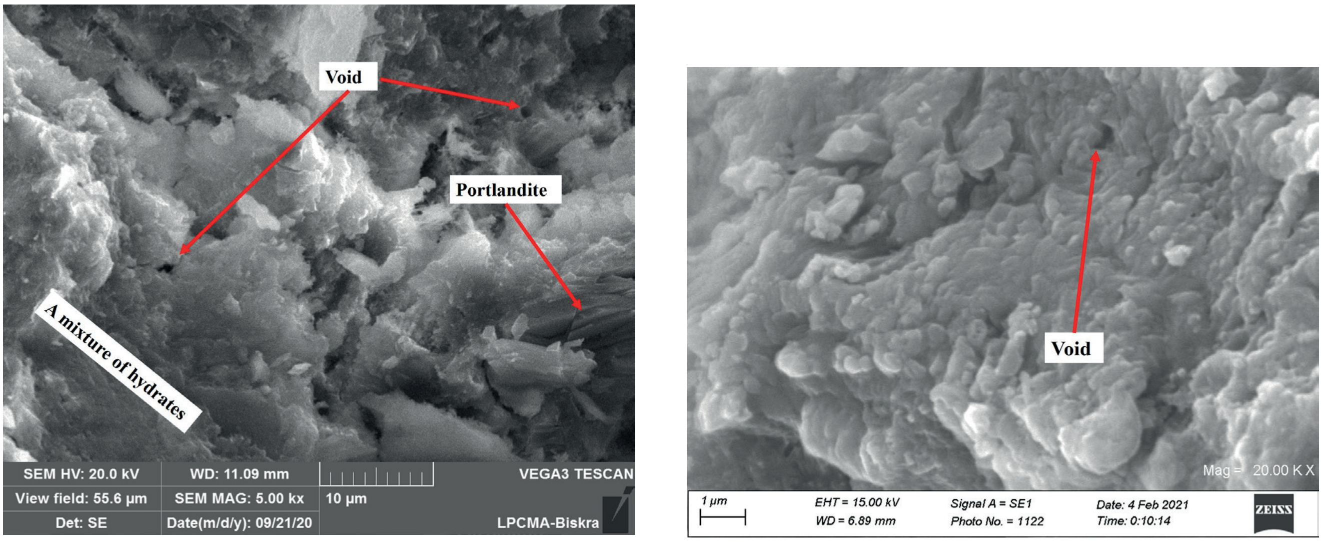
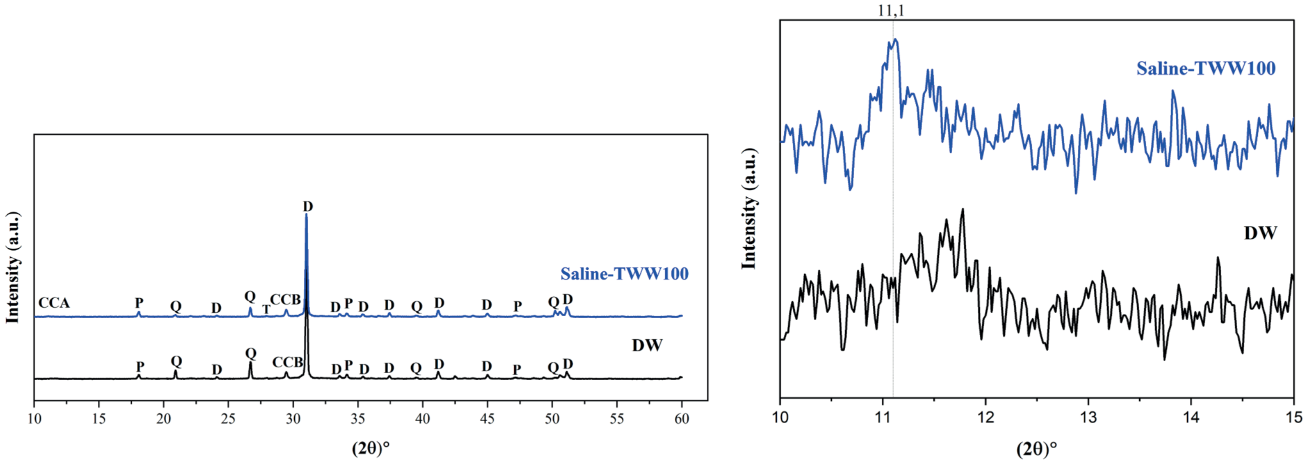


Fig. 7 SEM images of Saline-TWW100



(a)

(b)

Fig. 8 XRD profiles of salineTWW100 and DW concrete. (a) The XRD profiles between 10° and 60°; (b) The XRD profiles between 10° and 15°

This may have resulted in a higher amount of free chloride ions in the pore solution of saline-TWW paste, which may decrease the corrosion resistance of ordinary steel embedded in saline-TWW100.

3.5 Corrosion of steel

The steel corrosion in concrete is a severe threat that significantly reduces the safety and durability of structures and, consequently, leads to economic, environmental, and sustainability impacts [42]. In this study, a potentiodynamic polarization technique was conducted to investigate the magnitude of steel corrosion in reinforced mortar specimens made with saline-TWW and DW. Fig. 9 presents the Tafel curves for steel samples embedded in DW and saline-TWW mortars. The electrochemical characteristics obtained by the analysis of Tafel curves are shown in Table 6. The analysis of the results presented in Table 6 and Fig. 9 implies that increasing the percentage of saline-TWW as a replacement of DW leads to an increase in current densities (I_{corr}) and a shift of the corrosion potentials (E_{corr}) towards the negative direction. It could also be observed that with the increase of the percentage of saline-TWW as replacement of DW, the polarization resistances (R_p) decrease, and the corrosion rates (V_{corr}) of reinforced steel increase gradually. This is mainly attributed to the higher admixed chlorides in the concrete mixes prepared using saline-TWW, which destroys the passivation film and increases mass charge transfer process and then the corrosion rate of embedded reinforcing steel of concrete. These observations may confirm the XRD results in the formation of low amounts of Friedel's salt in saline-TWW100 concrete. According to the RILEM TC 154-EMC [43] table of corrosion rate versus corrosion severity, embedded steel in DW concrete is in "low" corrosion level, while embedded steel in saline-TWW50 concrete is in "moderate" corrosion level. However, the embedded steel in saline-TWW100 concrete is in "high" corrosion level, indicating that the total replacement of DW by saline-TWW should be avoided for ordinary steel-reinforced concrete. This reduces the applicability of using 100% of saline-TWW as mixing water only for non-reinforced concrete. However, using a proper amount of some mineral admixtures can maximize the corrosion resistance of the concrete produced using saline-TWW. Further, the corrosion rate of steel in saline- TWW concrete can be avoided by using corrosion-resistant reinforcements. This can improve the usability of the saline-TWW and therefore result in a significant saving of potable water.

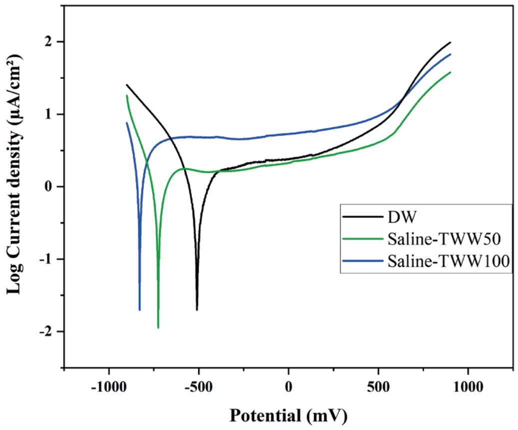


Fig. 9 Tafel curves for steel bars embedded in DW and saline-TWW concretes

Table 6 Electrochemical characteristics of steel

Mix Type	R_p (KΩ.cm^2)	β_a (mV)	β_c (mV)	I_{corr} (µA/cm^2)	-E_{corr} (mV)	V_{corr} (µA/year)
DW	54.40	135	93	0.332	513	3.88
Saline-TWW50	38.72	185	109	0.567	727	6.63
Saline-TWW100	15.09	128	77	1.046	831	12.24

4 Conclusions

This study aimed to investigate the use of treated wastewater containing high concentrations of dissolved salts as mixing waters for concrete. From the results of our experimental work, the following conclusions were drawn:

1. Due to the concentration of organic compounds, the setting times of cement paste were gradually increased with increasing the saline-TWW replacement percentage.
2. Increasing the percentage of saline-TWW in the concrete mixture gradually increased the 7-day compressive strength and decreased the 28-day compressive strength. However, the partial and total replacement of DW by saline-TWW for concrete mixing did not influence the long-term compressive strength of the concrete.
3. The partial and total replacement of DW by saline-TWW showed no significant effect on the workability of fresh concrete and a positive effect on the concrete permeability.
4. SEM images indicated that saline-TWW concrete exhibited a more compact microstructure and smaller pore sizes than their counterparts of DW.
5. The electrochemical test results indicated that the polarization resistance (R_p) decreases and the corrosion rate of reinforced steel (V_{corr}) increases gradually

with the increase of the percentage of saline-TWW as replacement of DW, indicating that the corrosion resistance of embedded reinforcing steel is lowering with the increase of the percentage of saline-TWW in the concrete mixture.

Based on the results of this experimental study, it can be finally concluded that the incorporation of saline-TWW used in this study at replacement percentages of 25% and 50% of freshwater can be authorized for concrete production, with acceptable fresh and hardened properties. However, using of 100% saline-TWW as mixing water should be avoided for ordinary steel-reinforced concrete because of the high possibility of corrosion. However, to improve its usability, additional tests are necessary to determine the effect of saline-TWW on other concrete mixtures prepared with other types of cement and using chemical and mineral admixtures.

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