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Review article

Seawater-mixed concretes containing natural and sea sand aggregates – A review

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ABSTRACT

In light of global warming and the rising urban population across the world, freshwater is becoming a scarce commodity. Freshwater consumption in the production of concrete makes up a significant (9%) share of total freshwater withdrawal for industrial purposes. Among the alternative sources of water for concrete production, seawater involves minimal processing, besides screening debris with filters. Other options, such as the use of wastewater from industrial effluent or desalination of hard waters, require a significant amount of energy, which add to overall concrete production emissions. Many efforts have been made by researchers in the last decades to understand the behaviour of seawater-mixed and sea sand concretes (SW-SS). The present work evaluates the early-age hydration, fresh, mechanical, and durability performance of SW-SS concretes and the corrosion characteristics of embedded reinforcement in them. The authors also summarize mitigation measures recommended in the literature for improving the anti-corrosion performance of SW-SS concretes, by partial substitution of supplementary cementitious materials (SCMs), the inclusion of alternative reinforcements (such as stainless steel and fibre reinforced polymer bars), the incorporation of corrosion inhibitors, and the adaptation of cathodic prevention measures. Finally, the article highlights the possible challenges to, opportunities for and potential applications of SW-SS concretes in the near future, so as to combat the freshwater crisis in nations suffering severe water stress.

1. Introduction

The UN-Water Policy Brief states that improving the resilience of freshwater ecosystems is essential in adapting to climate change [1]. Freshwater is one of Earth's most precious resources, sustaining ecosystems, economies, biodiversity, and society. Based on United Nations (UN) General Assembly resolution 71/222, UN member states have adopted 2018–2028 as the international decade of Water Sustainable Development [1]. However, despite such initiatives poor water management strategies worldwide have led to inadequate access to safe drinking water for about 885 million people [2]. According to the Water Resources Institute (USA) "17 countries in the world face extremely high levels of stress," which indicates the severity of declining freshwater resources in these countries. Among freshwater withdrawals for industrial purposes, 9% is used for producing concrete globally [3]. Furthermore, 75% of total freshwater withdrawals for concrete production occur in regions experiencing severe water stress [3]. Under these circumstances, using freshwater or potable water for concrete-making and curing processes in regions of extreme water stress, should be substituted with alternative or non-potable water.

The use of non-potable water sources for concrete mixing is regulated by prescribed limits on water quality parameters, such as the amount of chlorides, sulphates, total solids, total alkali content, total suspended solids, and pH [4]. Gokulnathan et al. (2021) [5] have summarized the recommended water quality parameters for concrete mixing present in several international standards. Accordingly, the strength and fresh property performance requirements of concrete made with non-potable water, shall not be more than 5 – 10% worse than that of concrete mixed with fresh water [6]. Most alternative sources of non-potable water, such as industrial wastewater, domestic sewage water, and washing water, require extensive treatment to remove harmful chemicals that can affect the hydrated cement phases in concrete [6,7]. Among the alternative sources of water, the usage of seawater in concrete production has, in recent decades, gained the attention of concrete technologists.

Seawater is a natural resource that does not require any treatment

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processes, other than filtering out floating debris, nor transportation charges near coastlines, and can thus be a suitable alternative to freshwater in concrete. However, the amount of chlorides and sulphates in seawater is much higher than the limits proposed by several international standards [8]. EN 1008 recommends that the maximum chloride content for prestressed concrete or grout, reinforced concrete with embedded steel, and plain concrete without reinforcement, should be lower or equal to 500 mg/L, 1000 mg/L, and 4500 mg/L, respectively. An Indian standard for plain and reinforced concrete (IS 456:2000) states that the permissible limits for chloride and sulphate ions in mixing water should not be greater than 500 and 400 mg/L, respectively. However, worldwide the concentration of chloride ions in seawater can be between 10000 mg/L and 26000 mg/L [9]. The presence of chloride ions in seawater can result in chloride-induced corrosion in the embedded steel of reinforced concrete exposed to certain conditions. Furthermore, the supersaturation of sulphate and chloride salts in the pore solution of a cementitious matrix can induce cracks due to physical salt attack. To mitigate these negative effects, special mix designs and additives are often used in the production of seawater-mixed concrete. Pozzolanic materials, such as fly ash, slag, and metakaolin can enhance the strength and durability properties of concrete mixed with salts. Superplasticizers, which are chemical admixtures, can be added to a mixture to improve the workability and fluidity of concrete. Chemical admixtures can also be added to a mixture to reduce the setting time of the concrete and to increase its durability.

Fig. 1 highlights the increase in research interest on the topic of seawater-mixed concrete and concrete exposed to seawater, in the last few decades. The result of an article search across research databases with the string ‘concrete and seawater’, includes articles related to concretes exposed to seawater, concretes cured with seawater, and seawater-mixed concretes. Fig. 1 (b) shows that 90% of publications are related to seawater-exposed or cured concretes, with the remaining 10% related to seawater-mixed and sea sand concretes with alternative reinforcements. The articles related to concretes exposed or cured in seawater deal with the possible mechanisms of ingress of aggressive ions in seawater, the repair and rehabilitation of marine structures subjected to chloride or sulphate attack, and preventive maintenance strategies for improving the service life of reinforced concretes in marine environments. Fig. 1 (c) highlights the rapid increase in research publications related to seawater-sea sand mixed concretes (SW-SS).

Several researchers have studied the effects of partial and full replacement of fine and coarse aggregates, derived from riverbeds and quarries, with sea sand, dredged sand, coral sand, and coral aggregates locally available in the coastal environment [10–14]. These sands are rich in chloride and sulphate salts, which might have the same effects as using seawater in concrete mixing [15]. Furthermore, a significant amount of recent research has focused on using alternative reinforcement for concretes mixed with seawater and exposed to marine environments [16,17]. The development of special reinforcement bars, such as fibre-reinforced polymer (FRP) bars, stainless steel (Ss), and epoxy/cement-coated (EC/CC) rebars, could enable the use of seawater and sea sand in concretes, by circumventing the chloride limits proposed in international standards for producing reinforced concretes. Moreover, the addition of nano particles in SW-SS cementitious systems can enhance their mechanical performance and corrosion resistance [18–20]. Among these broad categories, the present work focuses on understanding seawater-mixed and sea sand (SW-SS) concretes (including dredged sand, coral sand, and coral aggregates).

Fig. 2 shows an in-depth analysis of raw materials used in various articles related to SW-SS concretes. CEM I 42.5 (Ordinary Portland Cement) is the most common cement type used for preparing SW-SS concrete specimens. Besides CEM I, CEM II, and CEM III, Portland composite cements (PCC) and calcium sulfoaluminate cements (CSA) are used for making cement paste, mortar, and concrete specimens. Fly ash, blast furnace slag, metakaolin, and silica fume are the most common types of supplementary cementitious materials (SCMs) used for producing SW-SS concretes. Researchers have also used alkali-activated cements based on slag and fly ash for producing SW-SS concretes. River sand, sea sand, coral sand, and marine sand are used as fine aggregates in producing SW-SS concrete, while crushed granite, coral aggregate, and gravel are used as coarse aggregates. Many research articles have outlined the benefits of using alternative reinforcements, such as glass fibre reinforced polymer (GFRP), carbon fibre reinforced polymer (CFRP), basalt fibre reinforced polymer (BFRP), and stainless-steel bars or wraps, to mitigate the serious threat of chloride-induced corrosion that prevails in typical carbon steel reinforcement.

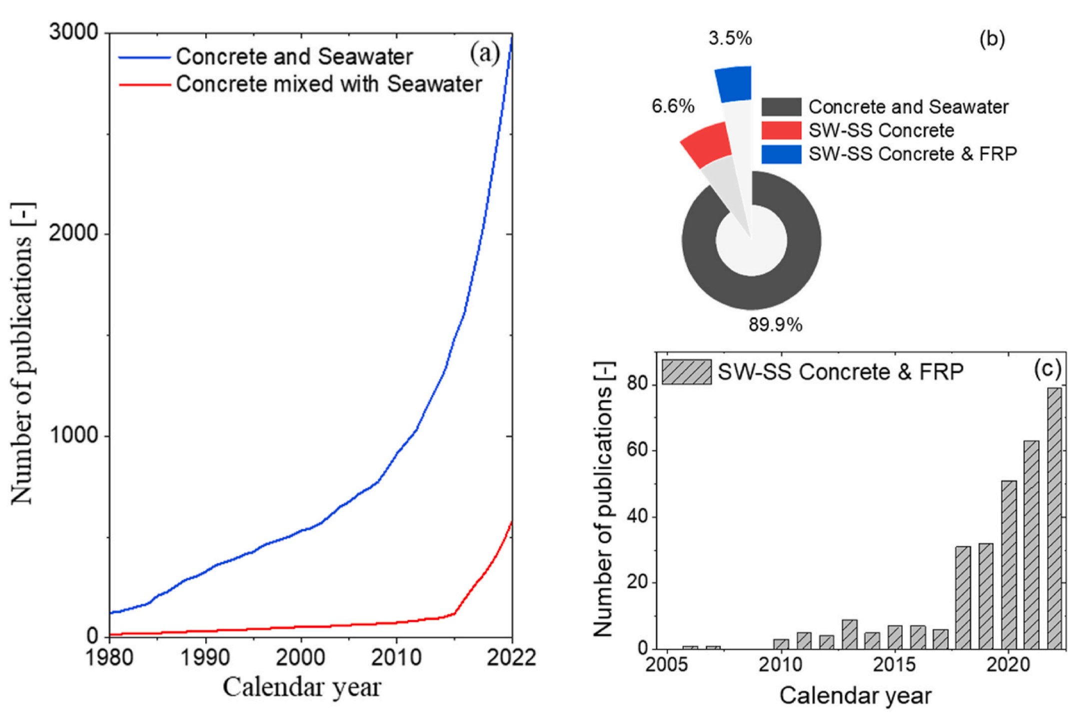


Fig. 1. Year wise publications on concretes exposed to seawater and seawater-mixed concretes [Source: Scopus database].

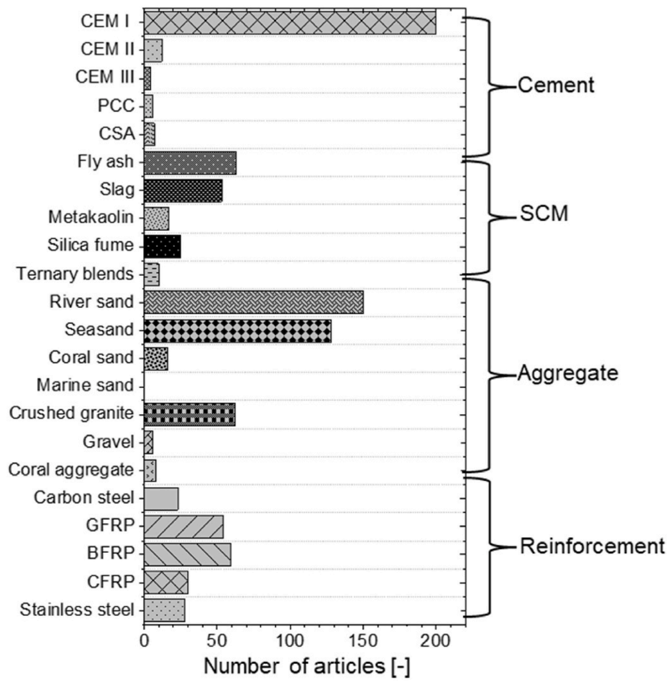


Fig. 2. Raw materials used in SW-SS concretes according to the available literature.

Fig. 3 shows the geographical distribution of research articles related to SW-SS concretes. Countries which have been producing research publications related to SW-SS concrete, such as China, the USA, India, Indonesia, Australia, Qatar, and Egypt, will also face high or extremely severe water stress by 2040, according to estimates made by the World Resources Institute [21]. Thus, the need to develop a sustainable solution for producing concrete mixed with seawater, through the appropriate use of SCMs, alternative aggregates, and special reinforcements, is being realized by these countries. As such, the increase in research interest related to SW-SS concretes is clearly justified.

Previous review articles have highlighted the early-age hydration and microstructural development, flow characteristics, and mechanical properties of SW-SS concretes [22–24]. However, in the following sections, this paper focuses on quantifying the effects of seawater mixing, and the substitution of sea sand and coral aggregates for natural aggregates, on the properties of SW-SS. Furthermore, the article includes a meta-analysis of data from tests assessing the strength and fresh properties of SW-SS concretes, in published articles. Also, the effects of salts from seawater, sea sand, and coral aggregates, on the long-term durability of seawater-mixed and sea sand (SW-SS) concretes, are critically reviewed. In conclusion, the perceptions, challenges, and possible niche applications in the use of SW or SS concretes are summarized.

2. Seawater-mixed and sea sand concretes

2.1. Early age hydration and microstructure

Seawater is a complex mixture of water, salts, particulates, and traces of organic materials. Worldwide, the major constituents of seawater are chloride, sodium, sulphate, magnesium, calcium, and potassium ions [25]. The interaction of these ions with hydrated cementitious systems needs to be understood, in order to study seawater concrete's hydration at an early age. The presence of higher amounts of bound water and calcium hydroxide in cementitious pastes produced with seawater, could be attributed to an acceleration of hydration reactions at an early age [26]. Wang et al. [27] have observed a denser and stronger hydrated cement matrix in seawater cement paste, compared to de-ionized water-cement paste. Also, seawater cement pastes have a higher ratio of fine porosity and a narrower width of the interfacial transition zone (ITZ), compared to freshwater systems [28]. This decrease in porosity could be attributed to the accelerated formation of Al-Tobermorite (C–S–H) which fills the microstructure in the early days [26,29]. Seawater-mixed concretes have been found to exhibit better mechanical performance than conventional concrete at early ages and reduced strength at later ages [30]. The pore solution of a seawater system has three to four times greater ionic strength than a freshwater system [26]. An increase in the salinity of mixing water enhances the rate of hydration heat generation and increases cumulative heat generation during

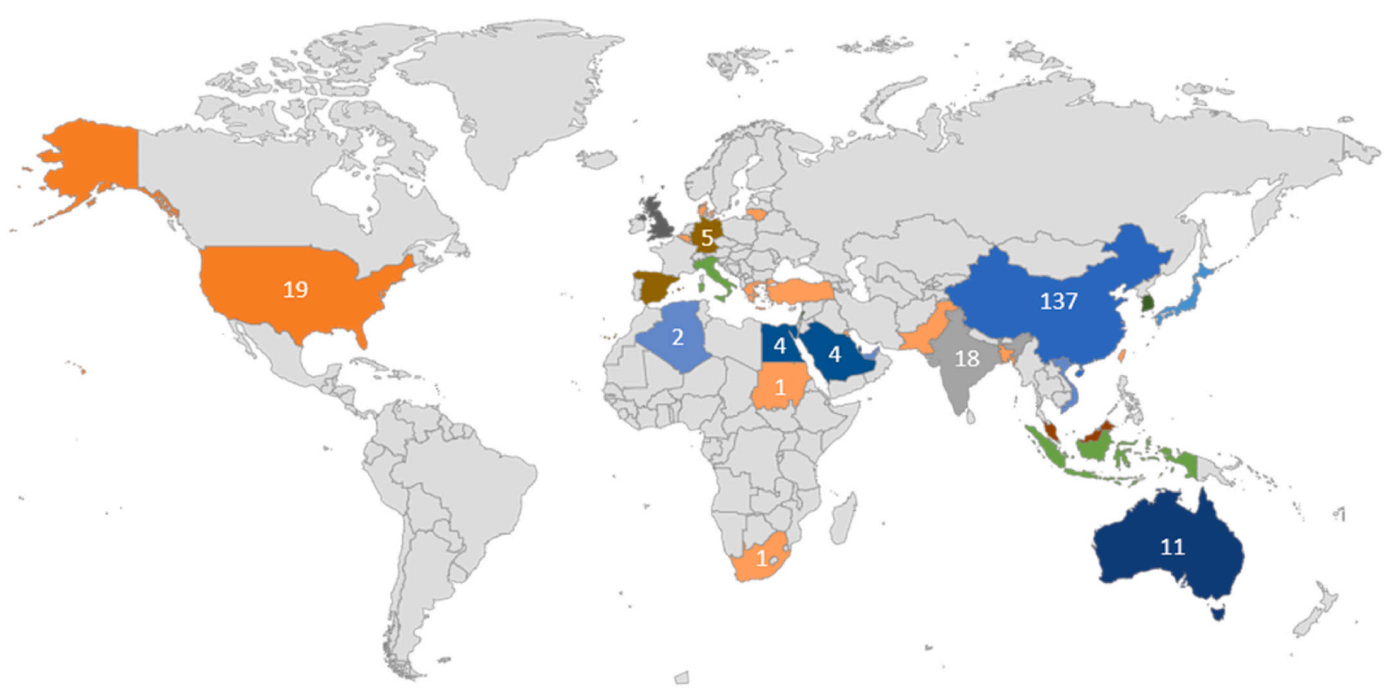


Fig. 3. Geographic distribution of publications related to SW-SS concretes.

hydration [31].

The presence of Cl^- ions induces Friedel's salt formation when they combine with calcium aluminium hydrates, through absorption or ion-exchange mechanisms [22]. Friedel's salt binds chlorides in the cementitious matrix and reduces the amount of available free chlorides necessary for corrosion initiation in the embedded steel. However, Friedel's salt formation at later ages is diminished due to the physical adsorption of chlorides in the C–S–H interlayers [26]. The incorporation of chloride and sodium ions in C–S–H interlayers shortens chain length compared to C–S–H made with deionized water [32]. The higher chloride concentration in the cement matrix reacts with calcium hydroxide and produces calcium oxychloride. Calcium oxychloride is 303% larger than calcium hydroxide in the cementitious matrix, leading to volumetric expansion [22]. The presence of sulphate and carbonate ions in the pore solution negatively affects the chloride binding ability of the cementitious matrix. Conversely, cations in the pore solutions, such as calcium and magnesium, can improve the binding ability of cementitious systems [11]. The interaction of these ions with cementitious systems results in an increase in early age compressive strength, a higher heat of hydration, increased shrinkage, and a shortened setting time.

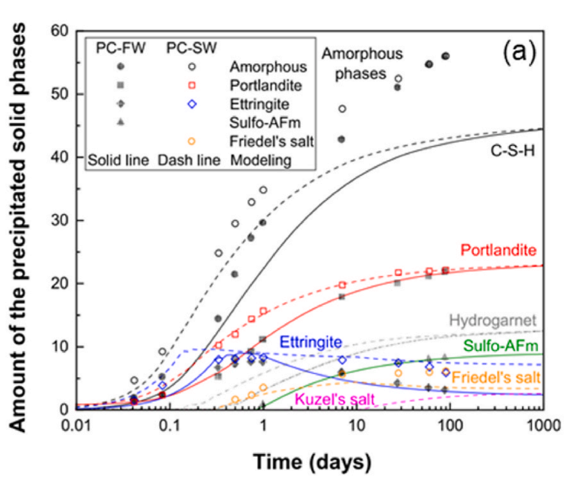
Fig. 4 (a) shows the thermodynamic prediction of the evolution of hydrated phases over time, in Portland cement systems mixed with fresh and seawater. It is a clear indication of an increase in the quantity of major hydrated phases, such as amorphous C–S–H, hydrogarnet, and portlandite, at early age (< 10 days), in both experimental and model estimations. Also, cement pastes mixed with seawater consist of ettringite, Fridel's salt, and Kuzel's salt, instead of the monosulphate phases abundant in freshwater mixed cement pastes. This could be attributed to the excess supply of sulphates in seawater and the chemical binding of chlorides in hydrated phases. Fig. 4 (b) indicates an increase in the solid phases by 3.7% for seawater pastes and a decrease in the liquid phases by 12.2%, based on thermodynamic modelling in cement paste made with CEM I [33].

The partial substitution of clinker/CEM I with supplementary cementitious systems can further improve the durability and sustainability of SW-SS concretes [34–36]. The addition of SCMs to seawater-mixed pastes can alter the formation of additional hydrated phases due to the pozzolanic reaction and thus enhance the immobilization of chloride through binding [37,38]. The presence of metakaolin in seawater cement pastes encourages the formation of hydrocalumite, in addition to ettringite and Friedel's salt [39,40]. Similarly, alkali-activated slag systems produce calcium aluminate hydrate phases, in addition to hydrocalumite, due to the presence of a higher alumina content (>15%) [41]. Also, the incorporation of silica fume at lower contents in seawater cement pastes can enhance the hydration rate, compared to the presence of slag at higher concentrations (>50%) [42]. The addition of fly ash to seawater cement pastes results in denser C–S–H gels, compared to OPC pastes, but the total quantity of C–S–H gels is reduced with the higher replacement level of fly ash (45%) due to a decrease in OPC content [43]. The addition of limestone calcined clay can promote the formation of Friedel's salt and thereby further refine the porosity of seawater-mixed cementitious systems [43,44]. The incorporation of waste glass powder in SW-mixed cementitious systems can increase the hardness of the C–S–H produced, while the presence of ions in waste glass powder also enhances the acceleration of cement hydration [45]. In addition, seawater-mixed cementitious systems with nano silica refine the microstructure of the cement matrix, and the synergy between nano silica and seawater can enhance resistance to the transport of aggressive ions through the cementitious matrix [46]. More research is required to understand the combined effects of the addition of SCMs and seawater, in the hydration processes of cementitious and alkali-activated systems [23].

2.2. *Fresh properties*

The presence of chlorides in seawater accelerates the setting time of seawater-mixed cement pastes. The accelerating effect of seawater in cementitious systems has an impact on the flow characteristics of seawater-mixed concrete [27]. The initial slump flow of concrete mixed with seawater is 20% lower compared to concrete mixed with freshwater [47]. The presence of suspended solids in seawater leads to a decrease in packing density in seawater-mixed cementitious systems, compared to freshwater cementitious systems [48,49]. In addition to the flow characteristics mentioned above, the rheological properties of seawater cement pastes have also been evaluated [48,50]. Water film thickness (WFT) is a rheological parameter (being the ratio of excess water to the total surface area of solid particles) that governs the flow rate and adhesiveness of cement paste systems. In SW cement pastes, the WFT is lower than in freshwater-mixed (FW) cement pastes, due to lower packing density [48]. The plastic viscosity and yield stress of seawater cement pastes are higher than those of freshwater cement pastes, due to the presence of suspended solids in the mixing water [50]. Furthermore, the increase in viscosity and yield stress is significantly higher in fly ash mixes, due to the presence of more aluminium phases that bind the chloride ions to Friedel's salt [50]. Compared to freshwater cementitious systems, the thixotropic behaviour of SW-mixed cement pastes is higher, due to the increased probability of flocculation of cement clusters as a result of the high concentration of salts in seawater [50].

Fig. 5 (a) summarizes the percentage changes in the fresh properties, such as slump, spread, packing density, viscosity, water film thickness, thixotropic area, and yield stress, of SW-SS concretes with and without superplasticizers. A clear indication of a decrease in slump, flow spread,



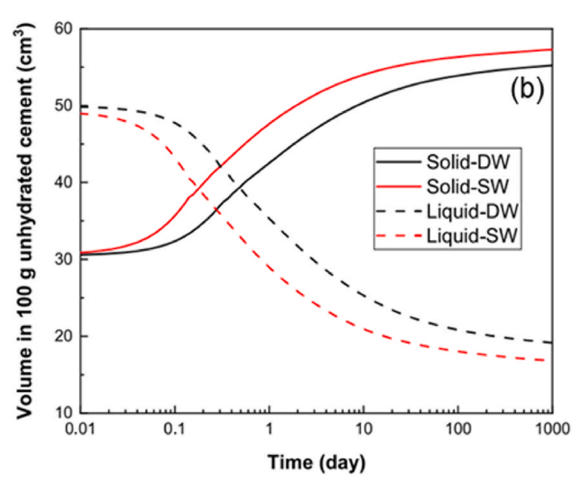


Fig. 4. Evolution of hydrated phases of cement mixed with seawater and freshwater [33]. Reproduced with permission of Elsevier, 2023.

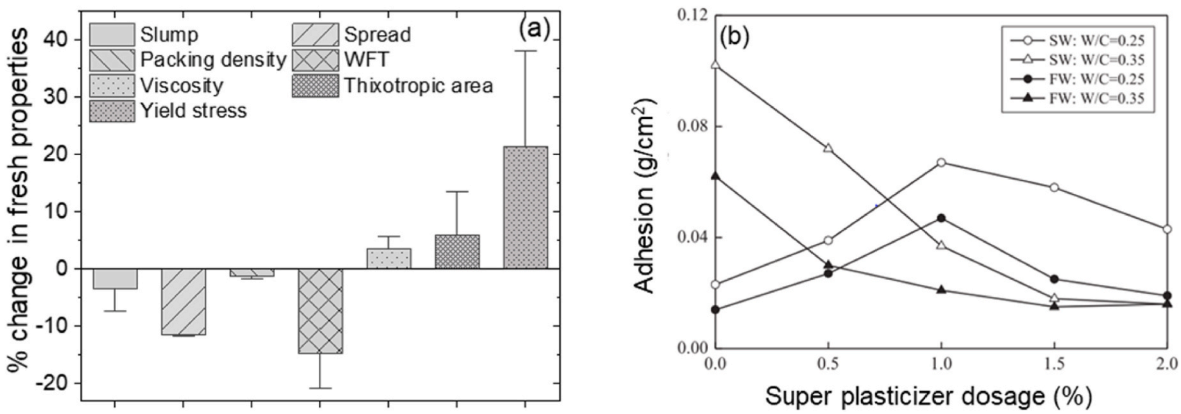


Fig. 5. Influence of seawater-mixing on fresh and rheological properties (a) [47–50] and the role of superplasticizer dosage on paste adhesion (b) Reproduced with permission of Elsevier, 2023 [48].

packing density, and WFT, and an increase in viscosity, yield stress, and thixotropic area, has been demonstrated in the literature [47–50]. In SW cement pastes, the addition of poly-carboxylate ether (PCE)-based superplasticizer can improve absorption efficiency, due to complexation between carboxylate groups in PCE and divalent ions in seawater [45]. Fig. 5 (b) shows the influence of superplasticizer on the adhesiveness of freshwater and seawater-mixed cement pastes. The high adhesiveness in seawater pastes could be attributed to the acceleration of cement hydration and the viscosity of seawater pastes [49]. Furthermore, the stability and rapid setting of underwater concreting could be improved by using seawater cement pastes, along with anti-washout admixtures, such as polyacrylamide (PAM), that significantly enhance the viscosity of cement paste. Between the two dosages of PAM (0.5 & 1% by weight of water), cement pastes with 1% PAM have a higher viscosity and offer higher resistance against the washout loss that could occur in under-sea construction [49]. The fresh properties of SW-mixed cementitious systems can be affected by adding suitable chemical admixtures to achieve the desired performance. The rheological characteristics of SW-SS cementitious systems made with different SCMs are yet to be explored, so as to understand the interaction between the suspended solids in seawater, or sea sand and hydrated cement phases.

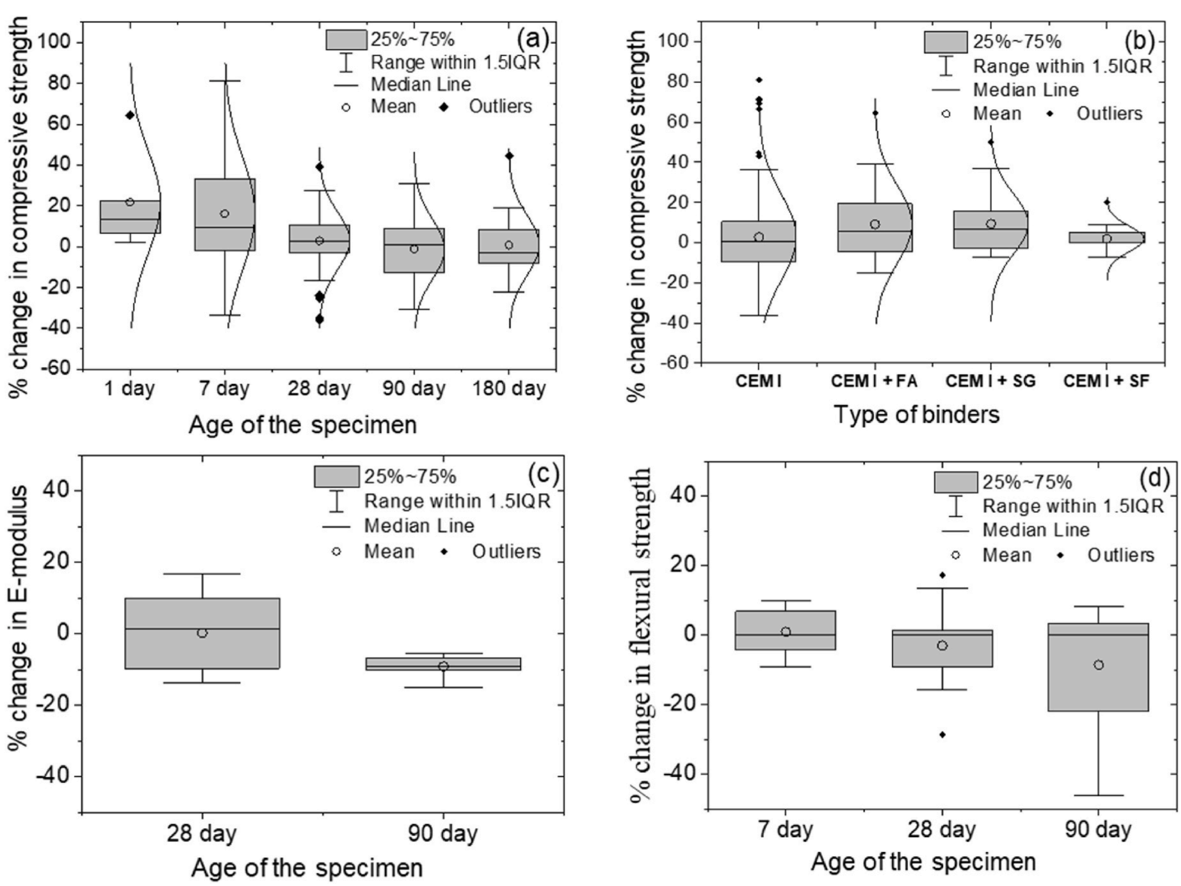


Fig. 6. Effects of seawater mixing on the mechanical properties of concrete: % change in compressive strength – (a) Age of specimen; (b) Binder type; (c) % change in Elastic modulus; (d) % change in flexural strength [55,57–66].

2.3. Mechanical strength and dimensional stability

SW-SS concretes develop notably higher compressive strengths than FW concretes, after 28 days of moist curing [26,51–53]. In general, the percentage increase in the compressive strength of SW-SS concrete is reported to be as high as 75% after 7 days and less than 10% after 180 days [53]. However, the results in the literature about the later-age strength of SW-SS concrete are contradictory and inconclusive [52]. Also, the influence of the salinity of seawater and concrete composition including type of cement, aggregates, and replacement levels of SCMs are not investigated adequate in the existing literature. Moreover, the level of salinity in seawater can influence the compressive strength of SW-SS concretes positively at early ages of up to 7 days, but slightly negatively after 14 days of casting [31,50,54]. Also, the higher salinity of mixing water can increase shrinkage strain at 90 days, compared to mortars mixed with fresh water [31]. The optimum replacement level of silica fume for achieving an improvement in the compressive strength of SW-SS concrete is 12% [55]. C–S–H gels with seawater mixing achieve a finer microstructure, with gel pore sizes less than 5 nm, leading to a higher elastic modulus value in the seawater concrete than in normal water concretes. Tensile strength at 28 days is reported to have increased by 10–20% in concretes mixed and cured with seawater [56].

Fig. 6 (a–d) shows the evolution of the compressive strength, elastic modulus, and flexural strength of SW-SS concretes, with respect to time and binder type. The percentage (%) change in the above-mentioned hardened properties of SW-SS and FW concretes was calculated by collecting data from various articles [55,57–66]. The box plots present the distribution (represented by lines indicating the 1.5 $\times$ inter quartile range (IQR)) of the % change in the hardened properties of the concrete. These plots also highlight improvements in the mechanical properties of the SW-SS concretes in the early days of hydration and their reduction at a later age. It is the median values of the percentage changes in compressive, flexural strength, and e-modulus that should be taken into consideration, as there was an asymmetrical distribution of data across the positive and negative quadrants. Also, the addition of SCMs resulted in a better improvement in the percentage increase in compressive strength, compared to SW-SS concretes made with OPC. Among the binder combinations considered, CEM I + fly ash (FA) performed better than SW-SS concretes produced with CEM I + blast furnace slag (SG), or CEM I + silica fume (SF).

Yang et al. [67] have suggested that the higher drying shrinkage in seawater concretes, at early ages, is due to the higher paste content than in concrete produced with freshwater. Despite the density of SW and FW concrete being the same, the presence of suspended solids and the acceleration in hydration can marginally increase the paste content of the former in comparison to the latter [67]. Also, the increase in drying shrinkage strain of SW-mixed concretes can be attributed to the formation of a finer pore structure, due to accelerated hydration at an early age induced by the presence of chlorides [68]. The addition of fly ash in SW concretes might further increase drying shrinkage, because of the finer pore structure resulting from the synergy between seawater and fly ash during cement hydration [69]. However, the addition of fibres can reduce drying shrinkage in SW-mixed cementitious systems with SCMs, by restricting moisture movement and arresting shrinkage-induced cracking [51]. The density of concrete measured with ultrasonic pulse velocity (UPV), in both fresh and seawater, has been found to be almost the same [70]. Like conventional concretes, the density and other mechanical properties of recycled aggregate concrete, made with SW, does not decrease below 5–15% [71]. However, more research is required to understand the density and shrinkage behaviour of SW-SS concretes containing supplementary cementitious materials.

2.4. Durability

The presence of sodium chloride in seawater can improve the pH of the cementitious matrix by increasing the hydroxyl ion concentration, thus improving the likelihood of an alkali-aggregate reaction (AAR) in the presence of reactive aggregate [72]. However, the role of seawater in increasing the likelihood of AAR is not significant in the presence of reactive aggregates at elevated temperatures [73]. The freeze-thaw resistance of SW-SS concrete has been found to be higher compared to ordinary concrete mixed with freshwater and made with river sand [74]. However, the addition of slag can improve the freeze thaw resistance of SW-SS concrete [11]. The water penetration depth of SW-SS concretes is less than that of ordinary concrete, due to the reaction between Friedel's salt and portlandite in the cementitious matrix, which forms $CaCl_2$ and improves the compactness of concrete [75]. Among SCMs, the water penetration resistance of SW-SS concretes substituted with fly ash does not improve, compared to those of concretes made with limestone calcined clay [75]. Also, the addition of rice husk ash, together with nano-silica and nano-alumina, improves water penetration resistance in SW-SS concrete [76]. The presence of chlorides and sulphates in seawater and sea sand is a major threat to the long-term durability of SW-SS concrete [77].

Fig. 7 (a) shows that the total diffused chlorides in SW concrete with SCMs, has been found to be less than the diffused chlorides in FW concrete, due to the higher chances of precipitation of Friedel's salt and ettringite in the pore system, which leads to pore refining [66]. However, the number of free chlorides in coral aggregate seawater concrete has been observed to be higher than in ordinary concrete after 120 days of immersion in seawater, with this potentially being due to the fact that coral aggregates are light weight and porous in nature [78]. Fig. 7 (b) shows the carbonation rates of concrete mixed with seawater and with tap water, which have been reported as being almost the same [79]. The incorporation of SCMs, such as fly ash, metakaolin and blast furnace slag in SW-SS concrete, has been reported to cause a decrease in the penetrability of chloride ions through the refined pore structure of the cementitious matrix, due to the filling effect, pozzolanic reaction, and seawater accelerated hydration due to seawater-mixing [79,80]. SW-SS concretes with a higher replacement of BFS and fly ash have an increased resistance to oxygen permeability, but a decreased resistance to carbonation [79]. The initial presence of chloride in SW-SS concretes can influence the results of rapid chloride migration tests and thus silver nitrate solution cannot be used for observing chloride profiles [80]. New indicators based on K_2SWO_8 and H_2O_2 have been proposed for use in rapid chloride migration (RCM) tests, for both concretes contaminated with chlorides, as well as SW-SS concretes [81]. More research on the durability of SW-SS concretes needs to be conducted to evaluate their durability parameters and to predict the long-term performance of these concretes in aggressive environments containing chlorides, sulphates, moisture, and carbon dioxide.

2.5. Corrosion characteristics

Corrosion of steel is the major roadblock in the implementation of SW-SS concretes. Kaushik and Islam [82] have recommended that seawater not be used as mixing water for reinforced and prestressed concretes, as they have observed an extremely high degree of deterioration in reinforced concrete with SW as mixing water, after 18 months of exposure. Active corrosion of steel embedded in SW-SS concrete has been observed, after two years of natural exposure, with a higher $[Cl^-/OH^-]$ ratio compared to concrete mixed with freshwater [11]. However, the use of seawater as mixing water for concrete was found to have a lesser influence on corrosion activity, compared to the use of seawater as curing water [83,84]. Also, the application of seawater-mixed reinforced concrete in seawater immersion conditions, does not result in any serious deterioration, even after 20 years of exposure [85]. Partial substitution of concrete with SCMs such as fly ash, slag, and silica fume has been recommended in order to produce a dense matrix which resists corrosion activity [85]. However, the addition of fly ash in larger quantities (>50%) can reduce the formation of Friedel's salt, due to the lesser availability of the clinker fraction, thus reducing

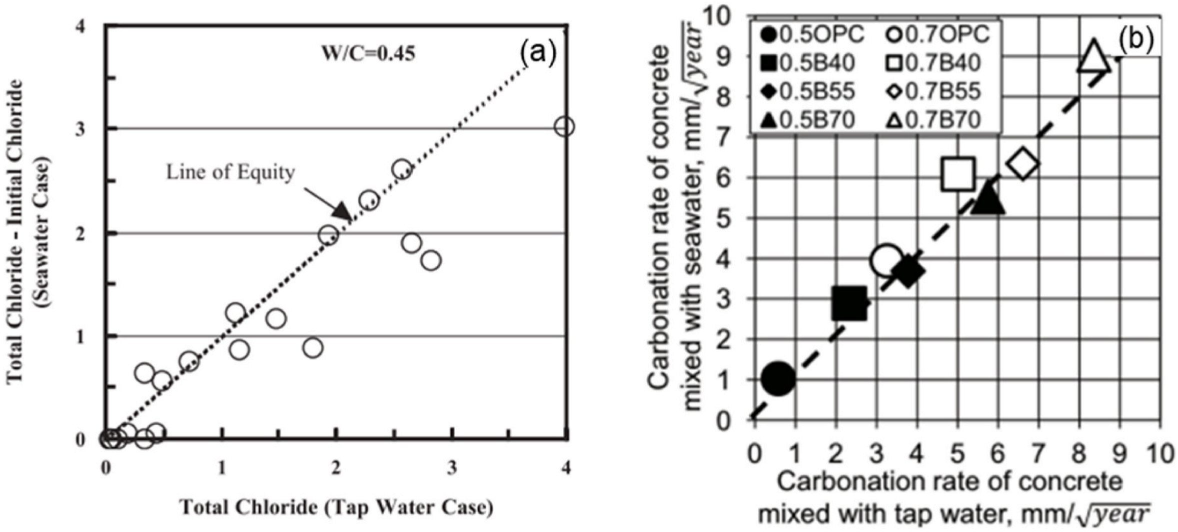


Fig. 7. Effect of seawater mixing on (a) chloride [66] and (b) carbonation ingress of concretes [79] Reproduced with permission of Elsevier, 2023.

the corrosion resistance of steel embedded in concrete. Conversely, lower corrosion rates have been observed in SW reinforced concrete specimens with 30% fly ash, compared to a higher replacement of 50% [86]. Among the typical SCMs, metakaolin-blended SW-SS concretes demonstrate better corrosion protection than fly ash and slag specimens, due to an enhancement in chloride binding capacity [87]. The presence of more chloride ions in SW-SS concretes can result in the formation of rust products which are more expansive than magnetite and haematite phases, like lepidocrocite (ϒ-FeOOH) and akaganite (β-FeOOH), in the layer of embedded-steel [88]. Service life assessment of SW-SS concretes with fly ash and slag, in regard to chloride-induced corrosion, has showed that the time for corrosion initiation is shorter and that the time for corrosion propagation is longer than for conventional concretes [79]. Thus, the sum of initiation and propagation time, as the total service life of seawater concrete, is marginally shorter compared to freshwater concretes. Table 1 summarizes the effects of seawater-mixing and sea sand addition on concrete properties, as well as the influence of the partial substitution of SCMs and fibres in SW-SS concretes.

3. Ensuring the durability of sw-ss concrete

From *Section 2* above, it can be summarized that the strength, fresh, and durability properties of SW-SS concrete are not inferior in any way, excluding a marginal reduction in workability and an increased risk of embedded-steel corrosion in reinforced concretes. Accordingly, in order to encourage the use of SW-SS concrete by enhancing corrosion resistance, the following approaches are justified: improving chloride binding, incorporating corrosion inhibitors, adapting cathodic protection techniques, and using special reinforcements such as FRP and stainless steel.

3.1. Chloride binding

Chloride binding in cementitious systems can occur through chemical binding in hydrated phases and physical adsorption in the C–S–H interlayers [89]. Fixed chloride ions in the cementitious matrix can have a lesser affinity for ion exchange with steel, compared to the free chlorides present in the pore solution [79]. In general, chloride binding capacity gradually increases with a decrease in the water-to-binder ratio from 0.4 to 0.2, at later ages [90]. Also, the chloride binding capacity can be significantly improved by the incorporation of metakaolin, compared to the addition of silica fume, due to the presence of higher Al-phases in the former [90]. The presence of higher Al_2O_3 phases in cement and SCMs has a positive impact on chloride binding capacity [91]. Furthermore, the incorporation of nano-Al_2O_3 by up to 4% can immobilize the chloride ions in the cementitious matrix, even at later ages [92,93]. Moreover, the addition of barium sulphate can enhance the fixation of chloride ions in hardened cement mortars by improving the dissolution of monosulphate in the presence of gypsum [94]. The addition of fumed silica can enhance the consumption of portlandite and densify the matrix, so that the free chlorides in it can be bound through physical adsorption on the C–S–H interlayers formed [95]. The role of sulphate availability in enhancing chloride binding has also been highlighted in the literature. The presence of higher sulphate ions in the solution can encourage the formation of ettringite, over the conversion of monosulphate to Friedel's salt [96].

The addition of an artificial aggregate made with CaO–$NaAlO_2$, by up to 5%, can improve chloride binding in cementitious systems by forming brucite, Friedel's salt, and Kuzel's salt [97,98]. The addition of clintophile (natural zeolite), along with an alkali-activated slag system, facilitates the binding of chloride and sulphate ions in the pore structure

Table 1
Effect of salts and ions in SW-SS concrete with SCMs and fibres.

Change in properties of concrete.	Early-age hydration		Fresh properties			Strength & E-modulus		Shrinkage	Long-term durability		
	Heat of hydration	Setting time	Slump/ Spread	Viscosity	Shear stress	Early age	Later-age		Water Permeability	Chloride resistance	Steel corrosion
Effect of salts present in SW-SS concrete	↑	↓	↓	↑	↑	↑	↔	↑	↑	↓	↓
Substituting SCMs in SW-SS concrete	↓	↑	↔	↔	↔	↑	↔	↑	↑	↑	↔
Addition of fibres in SW-SS concrete	↔	↔	↓	↑	↑	↑	↔	↓	↑	↑	n/a

Note: ↑- increases; ↔ - no difference; ↓- decreases; n/a – not applicable.

with the formation of Kuzel's salt [99]. Furthermore, the addition of mineral admixtures with calcium sulpho-aluminate cement pastes mixed with seawater, can improve the physical adsorption of chloride ions to the CSA pastes, corresponding to the ratio of Ca/Al [100]. More research on the optimum levels of mineral admixture additions and dosages of additives enhancing chloride binding, is required to produce seawater-mixed concrete with a longer service life against chloride-induced corrosion.

3.2. Corrosion inhibitor

Corrosion inhibitors are chemical admixtures added to a cementitious system to reduce free chlorides, which are responsible for initiating corrosion in embedded steel in concrete, in the pore solution. In SW-SS concretes, corrosion inhibitors such as imidazoline, at 0.75%, and triethylenetetramine, at 1%, have been used to extract chloride ions on the surface of steel rebars [101]. A combination of corrosion inhibitors, including triethanolamine, dimethylethanolamine, lithium nitrate, and ethenyl triethoxysilane, at a dosage of 1.5%, has been used to enhance the stability of the passive film of the rebar by adsorbing on its surface. The efficiency of this corrosion inhibitor in SW-SS is good enough to retard the corrosion process in cementitious systems with pre-mixed chlorides [102]. In coral aggregate concretes, the addition of aluminium tri-polyphosphate can improve the quality of the protective passive layer on the surface of steel bars, by increasing polarization resistance and interacting with hydration products, to form phases filling the concrete's micro and macro pores [63]. A novel corrosion inhibitor, made with silver nanoparticles, can be included in SW-SS concrete to block the diffusion of chloride ions at the level of the steel, by blocking capillary pores [103]. It is clear that corrosion inhibitors, together with the appropriately chosen reinforcement (as discussed in detail in Section 3.3), can improve the resistance of SW-SS concrete against corrosion-induced failure.

3.3. Special reinforcement

3.3.1. Stainless steel and coated rebars

The higher critical chloride threshold values of stainless steel over carbon steel, make it possible to use the former in SW-SS concrete with a higher initial chloride content [104]. Previous work has demonstrated the possibility of designing reinforced SW-SS concretes with a service life greater than 150 years, by providing a reasonable cover depth of 30–40 mm [105,106]. In alkaline conditions, the use of duplex stainless steel has been found to be feasible in SW-SS concrete, as a result of the presence of a stable passive layer at a very high chloride ion concentration of 2 M [107]. However, the reduction in pH, due to carbonation, can result in depassivation of embedded steel rebars. As such, more experiments are required to understand the effects of low pH on corrosion initiation in reinforcing steel within SW-SS concretes. The suitability of using low alloy steel rebars in SW-SS concrete has been evaluated and found to be suitable for use in concretes having a pre-mixed chloride content of less than 0.05 M [108]. Under stress corrosion cracking, austenitic stainless steel can be used in SW-SS concretes, even at a higher temperature of 60 °C, as no cracks occur at such exposure conditions [109]. Epoxy coated rebars should be avoided in SW-SS concretes, despite their higher chloride threshold, due to the possibility of pinholes or microdefects forming on the surface of the coating [110,111]. Such defects can lead to more severe crevice corrosion than the pitting corrosion expected to occur in chloride-induced corrosion [111]. Therefore, austenitic and duplex grade stainless-steels are suitable for SW-SS concretes, as their critical chloride threshold values are much higher than the chloride content in concrete mixed with seawater [112].

3.3.2. FRP rebars, tubes, and wraps

Fibre-reinforced polymers are made with fibres such as basalt, carbon, glass, and steel embedded in resin matrices such as epoxy, vinyl ester, and polyester [113]. Fig. 8 shows the FRP wraps, bars, and tubes that have been used in various SW-SS concretes [113,114]. Due to their mechanical properties, GFRP and BFRP rebars are the most commonly used FRP bars in concrete made with seawater and sea sand, for applications that require adequate corrosion resistance in severe exposure conditions [115–118]. Research has shown that the initiation of cracks caused by flexure in GFRP reinforced SW-SS beams can be mitigated, and that this leads to an increase in the ultimate bearing capacity of the beams [119]. CFRP bars exhibit better durability performance in aggressive environments such as alkaline cementitious matrices [120]. Combinations of steel-FRP composites and rebars (SFCB) are used in SW-SS concretes, and the bond performance of SFCB composites is superior to ordinary concretes made with river sand and natural aggregates [121]. In order to avoid poor performance, adequate care should be given to FRP composites by protecting them from aggressive exposure conditions, such as extreme temperature, moisture, and ultraviolet radiation [122]. The inclusion of BFRP needles, as an alternative to bars, can enhance the fracture toughness of SW-SS concrete beams without adverse effects on their other mechanical properties [123].

Composite tubes, with BFRP and CFRP wrap and steel tubes confining SW-SS concretes, have been developed to enhance the performance of SW-SS columns under axial compressive load [126]. In comparing BFRP and CFRP confinements, the former show better deformation effects, while the latter show better reinforcement effects; both enhance the ultimate stress and strain values of a column [126–128]. Partial confinement of SW-SS concrete with CFRP wraps also provides excellent protection against sudden failure, by improving lateral-to axial strain relationships [129]. Models have been developed to predict the long-term behaviour of such FRP confinements and composite beams under load and environmental effects [130,131]. There is a clear advantage in using FRP as an alternative reinforcement in SW-SS concretes in offshore structures, as the mechanical performance and durability of FRP composites have been thoroughly assessed in the existing literature.

3.4. Other techniques

Researchers have demonstrated the suitability of using cathodic protection and monitoring with anodes for improving the service life of reinforced concrete with carbon steel. An increase in charge transfer resistance and pH near the surface of a steel rebar decreases the corrosion rate of seawater concrete [132,133]. Also, the impressed current cathodic protection method has been used to impede further corrosion in SS concrete beams [134]. but more research is required to optimize such strategies, in order to protect SW-SS concrete beams reinforced with steel. Furthermore, steel, polyethylene, polyoxymethylene, polyvinyl alcohol, and sisal fibres are used in SW-SS concrete beams for producing ultra high-performance concretes, so as to improve their fresh, mechanical, microstructural, shrinkage, durability, and corrosion performance. Table 2 summarizes the materials and approaches available for enhancing the durability of SW-SS concretes. The durability of SW-SS concretes could be improved by enhancing chloride binding, using anti-corrosive alternate reinforcements, adapting corrosion prevention methodologies, and adding fibres to the cementitious matrix [135–141].

4. Perceptions, opportunities and benefits

Roman concrete produced with seawater mixing, over 2000 years ago on the coast of Italy, has generated considerable interest among scientists seeking to understand the mineralogy of the hydrated phases present in those systems, so as to create modern concrete with the same properties [142–146]. The combination of raw materials, including volcanic ash, lime clusters, and seawater, produce a denser matrix consisting of Al-Tobermorite, which resists the aggressive environment

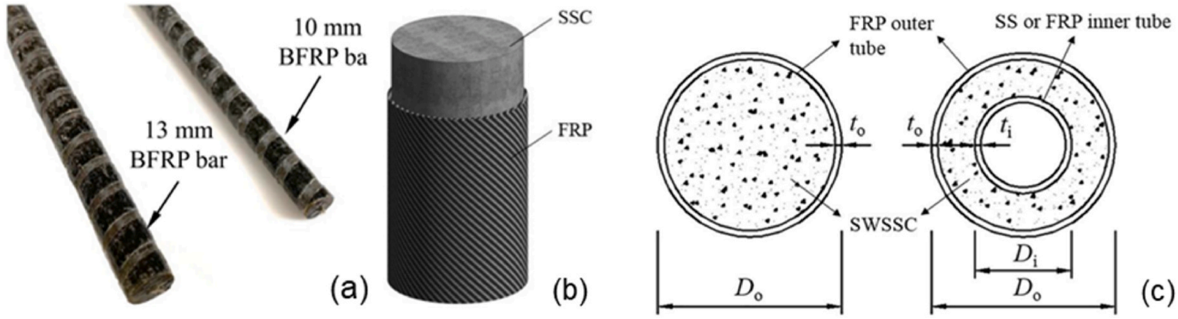


Fig. 8. FRP (a) bars (b) wraps; (c) Tubes/confinement [124–126], reproduced with permission from Elsevier 2023.

Table 2
Approaches for improving the durability of SW-SS concretes.

Approach	Materials and composites	Mechanism/Chemical reactions involved	References
Chloride binding	SCMs: Fly ash; Slag; Metakaolin, Silica fume, CSA, nano-Alumina,	The addition of SCMs containing alumina has influence on the ratio of Ca/Al of cementitious system. Optimum Ca/Al can improve chloride binding	[89,90,93,95, 99,100]
	Barium sulphate: 0–8% by weight of binder	Enhances the dissolution of hydrated phases and enables the fixation of Cl ions to form Friedel's salt	[94]
	CaO–$NaAlO_2$ at 5%	Dissolution of $NaAlO_2$ into Na^+ and Al $(OH)_4^-$ ions increases pH of the solution and then bind Cl^- ions	[97]
Corrosion inhibitor	Amino alcohol inhibitors	Controls the anodic and cathodic reactions at the level of steel	[101,102]
	Silver nanoparticles	Anticorrosion protective thin layer over steel bars.	[103]
	Aluminium tri-polyphosphate	Reacts with hydrated phases, fills micropores, enhances the density of cementitious matrix, and forms the protective layer around steel surface	[63]
Alternative reinforcements	Duplex (2304) stainless steel 316 L SS steel Austenitic SS	Critical threshold values greater than 3% by weight of binder – Very much higher than initial chloride content in SW-SS concretes.	[104–107]
	BFRP, CFRP, GFRP bars/wraps/tubes	Tensile, bond, and shear behaviour of FRP bars in SW-SS concretes are similar to the behaviour of rebars embedded in freshwater concrete. Anti-corrosive performance	[113,130]
Cathodic protection	Sacrificial anodes, Impressed current technique	Increase in the charge transfer resistance and local enrichment of OH ions and thus decreasing the corrosion potential	[132,134]
UHPC/ECC	Steel, polyethylene, polypropylene, polyoxymethylene, and Sisal fibres	Higher tensile strength, Improved fracture performance Better fatigue resistance Anti corrosive properties	[135–141]

of Italian seashores [144]. As such, the production of concrete with seawater is a major research interest among scientists, with the necessity to preserve freshwater resources providing the opportunity to produce sustainable concretes using seawater and mineral admixtures. Researchers have attempted to mimic the cementation mechanism of ancient roman concretes using calcined clays that shows the ongoing interest among people to produce concretes with seawater-mixing [147].

Fig. 9 summarizes the major challenges to, opportunities for, and applications of SW-SS concretes. The presence of steel in reinforced

Fig. 9. Summary of potential challenges to, opportunities for, and applications of SW-SS concretes.

concrete restricts the use of seawater-mixed concretes, due to higher salt contents which exceed the guideline values specified in the code of practice for making reinforced concretes. However, the development of advanced materials, such as ternary cementitious blends made with SCMs, nanoparticles, fibres, and alternative reinforcements, has made it possible to produce sustainable and durable concrete with alternative sources of water. Early-age seawater-mixed concrete hydration is currently being evaluated with advanced characterization techniques and modelling approaches, to optimize mix compositions utilizing supplementary cementitious materials [33,148]. Moreover, as demonstrated in Section 2.3, the mechanical properties of seawater-mixed and sea sand concretes do not drastically diminish at later ages. Furthermore, the fresh properties and durability characteristics of SW-SS and freshwater concretes are almost the same, besides the higher risk of reinforcement corrosion in SW-SS concretes.

The solutions available for improving the corrosion resistance of embedded steel, such as the inclusion of SCMs for improved binding and the use of alternative reinforcement in niche applications (light-weight SW-SS cement systems, FRP wrapped/confined SW-SS concretes, and temporary marine structures) could increase the applications of SW-SS concretes in the near future. For example, seawater-mixed concrete has been used to build seawalls, breakwaters, and jetties in many coastal areas [149]. Furthermore, SW-SS cementitious mortars shall be used for 3D printing applications without steel reinforcement and to improve the sustainability of those structures, by reducing their freshwater consumption, owing to their higher binder content. SW-SS concrete can be a suitable alternative for construction on remote islands where there are shortages of freshwater or river sand, as it can significantly reduce the water footprint and have a lower environmental impact, as compared to conventional concrete [19,150,151].

5. Conclusions

In conclusion, this article presented a meta-analysis of data collected from the literature pertaining to SW-SS concrete. Through thorough analysis of existing data in the literature, it is well established that the mechanical, fresh, and durability properties of SW-SS concretes are marginally reduced at later ages despite showing superior performance compared to freshwater concretes at an early age. Furthermore, the state-of-the-art shows that limited research is available on the long-term durability performance of SW-SS concrete, and more research in this area is needed to evaluate the suitability of SW-SS concretes made with SCMs. SW-SS concretes with FRP bars, wraps, and confinements showed better performance against the load and environmental effects compared to freshwater concretes with FRP reinforcement. Furthermore, approaches such as adding SCMs to enhance chloride binding, using corrosion inhibitors, and taking cathodic protection measures shall ensure the long-term durability of SW-SS concretes. Countries experiencing severe water stress and coastal nations shall benefit from using SW-SS concrete to preserve natural water resources, which are in short supply. Additionally, the development of standards and guidelines for producing concretes with seawater, sea sand, or coral aggregates shall be put forth in the upcoming years to ensure the durability of structures made with SW-SS concretes.

Credit author statement

Sundar Rathnarajan – Conceptualization; Formal analysis; Investigation; Project Administration; Visualization, Data Curation, Writing – Original draft; Pawel Sikora – Investigation; Supervision; Resources; Writing – 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.

Data availability

Data will be made available on request.

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References

[1] Climate Change and. Water -, UN Water Policy Brief, September 2019.
[2] WHO/UNICEF Joint water supply and Sanitation monitoring Programme, in: World Health Organization, UNICEF., Progress on drinking water and sanitation. 2012 update, UNICEF, 2012.
[3] S.A. Miller, A. Horvath, P.J.M. Monteiro, Impacts of booming concrete production on water resources worldwide, Nat. Sustain. 1 (2018) 69–76, https://doi.org/10.1038/s41893-017-0009-5.
[4] G. Reddy Babu, B. Madhusudana Reddy, N. Venkata Ramana, Quality of mixing water in cement concrete "a review, Mater. Today Proc. 5 (2018) 1313–1320, https://doi.org/10.1016/j.matpr.2017.11.216.
[5] V. Gokulanathan, K. Arun, P. Priyadharshini, Fresh and hardened properties of five non-potable water mixed and cured concrete: a comprehensive review, Construct. Build. Mater. 309 (2021), https://doi.org/10.1016/j.conbuildmat.2021.125089.
[6] M. Nikookar, N.A. Brake, M. Adesina, A. Rahman, T. Selvaratnam, Past, current, and future re-use of recycled non-potable water sources in concrete applications to reduce freshwater consumption- A Review, Cleaner Materials (2023), 100203, https://doi.org/10.1016/j.clema.2023.100203.
[7] S. Yousuf, P. Shafigh, Z.C. Muda, H.Y.B. Katman, A. Latif, Alternatives for fresh water in cement-based materials: a review, Water (Switzerland) (2023) 15, https://doi.org/10.3390/w15152828.
[8] Cement Concrete & Aggregates Australia Use of Recycled Water in Concrete Production, 2007.
[9] Y. Yi, D. Zhu, S. Guo, Z. Zhang, C. Shi, A review on the deterioration and approaches to enhance the durability of concrete in the marine environment, Cem. Concr. Compos. 113 (2020), https://doi.org/10.1016/j.cemconcomp.2020.103695.
[10] X. Qi, Y. Huang, X. Li, Z. Hu, J. Ying, D. Li, Mechanical properties of sea water sea sand coral concrete modified with different cement and fiber types, J Renew Mater 8 (2020) 915–937, https://doi.org/10.32604/jrm.2020.010991.
[11] Y.T. Li, L. Zhou, Y. Zhang, J.W. Cui, J. Shao, Study on long-term performance of concrete based on seawater, sea sand and coral sand, Adv. Mater. Res. (2013) 512–515, https://doi.org/10.4028/www.scientific.net/AMR.706-708.512.
[12] J. Liu, Z. Ou, W. Peng, T. Guo, W. Deng, Y. Chen, Literature review of coral concrete, Arabian J. Sci. Eng. 43 (2018) 1529–1541, https://doi.org/10.1007/s13369-017-2705-x.
[13] Vafaei, et al., Effects of Seawater and Sea Sand on Concrete Properties - A Review Paper. EASEC 16 101, 2021.
[14] Y. Cao, J. Bao, P. Zhang, Y. Sun, Y. Cui, A state-of-the-art review on the durability of seawater coral aggregate concrete exposed to marine environment, J. Build. Eng. 60 (2022), https://doi.org/10.1016/j.jobe.2022.105199.
[15] Y. Zhao, X. Hu, C. Shi, Z. Zhang, D. Zhu, A review on seawater sea-sand concrete: mixture proportion, hydration, microstructure and properties, Construct. Build. Mater. 295 (2021), https://doi.org/10.1016/j.conbuildmat.2021.123602.
[16] A. Ahmed, S. Guo, Z. Zhang, C. Shi, D. Zhu, A review on durability of fiber reinforced polymer (FRP) bars reinforced seawater sea sand concrete, Construct. Build. Mater. 256 (2020), https://doi.org/10.1016/j.conbuildmat.2020.119484.
[17] D. Wang, Q. Gong, Q. Yuan, S. Luo, Review of the properties of fiber-reinforced polymer-reinforced seawater–sea sand concrete, J. Mater. Civ. Eng. 33 (2021), https://doi.org/10.1061/(asce)mt.1943-5533.0003894.
[18] A.N. Saleh, A.A. Attar, O.K. Ahmed, S.S. Mustafa, Improving the thermal insulation and mechanical properties of concrete using Nano-SiO2, Results in Engineering 12 (2021) 3–5.
[19] P. Sikora, L. Afsar, S. Rathnarajan, M. Nikravan, S.Y. Chung, Seawater - mixed lightweight aggregate concretes with Dune sand , waste glass and nanosilica : experimental and life cycle analysis, Int J Concr Struct Mater (2023), https://doi.org/10.1186/s40069-023-00613-4.
[20] T. Kiran, D. Andrushia, C. El Hachem, B. Kanagaraj, A. N, M. Azab, Effect of nano cementitious composites on corrosion resistance and residual bond strength of concrete, Results in Engineering 18 (2023), https://doi.org/10.1016/j.rineng.2023.101064.
[21] T. Luo, R. Young, P. Reig, Aqueduct Projected Water Stress Country Rankings, 2015. http://www.wri.org/publication/aqueduct-projected-water-stress-country-rankings [accessed on September 2023].
[22] P. Li, W. Li, Z. Sun, L. Shen, D. Sheng, Development of sustainable concrete incorporating seawater: a critical review on cement hydration, microstructure

and mechanical strength, Cem. Concr. Compos. 121 (2021), https://doi.org/10.1016/j.cemconcomp.2021.104100.
[23] U. Ebead, D. Lau, F. Lollini, A. Nanni, P. Suraneni, T. Yu, A review of recent advances in the science and technology of seawater-mixed concrete, Cement Concr. Res. 152 (2022), https://doi.org/10.1016/j.cemconres.2021.106666.
[24] T. Dhondy, A. Remennikov, M.N. Shiekh, Benefits of using sea sand and seawater in concrete: a comprehensive review, Aust. J. Struct. Eng. 20 (2019) 280–289, https://doi.org/10.1080/13287982.2019.1659213.
[25] The Bahamas water scarcity Chemical and physical properties of seawater. https://www.britannica.com/print/article/531121 [Accessed on August 2023].
[26] L. Montanari, P. Suraneni, M. Tsui-Chang, M. Khatibmasjedi, U. Ebead, J. Weiss, A. Nanni, Hydration, pore solution, and porosity of cementitious pastes made with seawater, J. Mater. Civ. Eng. 31 (2019), https://doi.org/10.1061/(asce)mt.1943-5533.0002818.
[27] J. Wang, E. Liu, L. Li, Multiscale investigations on hydration mechanisms in seawater OPC paste, Construct. Build. Mater. 191 (2018) 891–903, https://doi.org/10.1016/j.conbuildmat.2018.10.010.
[28] P. Duan, W. Zhou, C. Yan, Investigation of pore structure and ITZ of concrete blended with mineral admixtures in a seawater environment, Mag. Concr. Res. 67 (2015) 812–820, https://doi.org/10.1680/macr.14.00282.
[29] M.W. Erniati, Zulharnah Tjaronge, U.R. Irfan, Porosity, pore size and compressive strength of self compacting concrete using sea water, in: Procedia Eng, Elsevier Ltd, 2015, pp. 832–837, https://doi.org/10.1016/j.proeng.2015.11.045.
[30] J. Xiao, C. Qiang, A. Nanni, K. Zhang, Use of sea-sand and seawater in concrete construction: current status and future opportunities, Construct. Build. Mater. 155 (2017) 1101–1111, https://doi.org/10.1016/j.conbuildmat.2017.08.130.
[31] T. Dhondy, Y. Xiang, T. Yu, J.G. Teng, Effects of mixing water salinity on the properties of concrete, Adv. Struct. Eng. 24 (2021) 1150–1160, https://doi.org/10.1177/1369433220965272.
[32] Y. Zhang, Y. Sun, P. Shen, J. Lu, Y. Cai, C.S. Poon, Physicochemical investigation of Portland cement pastes prepared and cured with seawater, Materials and Structures/Materiaux et Constructions 55 (2022), https://doi.org/10.1617/s11527-022-01991-z.
[33] P. Li, W. Li, K. Wang, J.L. Zhou, A. Castel, S. Zhang, S.P. Shah, Hydration of Portland cement with seawater toward concrete sustainability: phase evolution and thermodynamic modelling, Cem. Concr. Compos. 138 (2023), https://doi.org/10.1016/j.cemconcomp.2023.105007.
[34] S. Hwang, J.H. Yeon, Fly ash-added, seawater-mixed pervious concrete: compressive strength, permeability, and phosphorus removal, Materials 15 (2022), https://doi.org/10.3390/ma15041407.
[35] F. Hannanee Ahmad Zaidi, R. Ahmad, M. Mustafa Al Bakri Abdullah, W. Mastura, A. Syauqi, The effect of seawater on the strength, microstructure and elemental distribution of fly ash/Kaolin based underwater Geopolymer, in: IOP Conf Ser Mater Sci Eng, IOP Publishing Ltd, 2020, https://doi.org/10.1088/1757-899X/864/1/012014.
[36] G.B. RameshKumar, V.R. Mohamed Muzammil, Fly ash in concrete using sea water - a review, in: Mater Today Proc, Elsevier Ltd, 2020, pp. 890–893, https://doi.org/10.1016/j.matpr.2019.11.097.
[37] M. Antoni, J. Rossen, F. Martirena, K. Scrivener, Cement substitution by a combination of metakaolin and limestone, Cement Concr. Res. 42 (2012) 1579–1589.
[38] R. Homayoonmehr, A.A. Ramezanianpour, M. Mirdarsoltany, Influence of metakaolin on fresh properties, mechanical properties and corrosion resistance of concrete and its sustainability issues: a review, J. Build. Eng. 44 (2021), 103011, https://doi.org/10.1016/j.jobe.2021.103011.
[39] Q. Li, H. Geng, Z. Shui, Y. Huang, Effect of metakaolin addition and seawater mixing on the properties and hydration of concrete, Appl. Clay Sci. 115 (2015) 51–60, https://doi.org/10.1016/j.clay.2015.06.043.
[40] Z. Shi, Z. Shui, Q. Li, H. Geng, Combined effect of metakaolin and sea water on performance and microstructures of concrete, Construct. Build. Mater. 74 (2015) 57–64, https://doi.org/10.1016/j.conbuildmat.2014.10.023.
[41] Y. Jun, J.H. Kim, S.H. Han, T. Kim, Influence of seawater on alkali-activated slag concrete, Materials and Structures/Materiaux et Constructions 54 (2021), https://doi.org/10.1617/s11527-021-01719-5.
[42] H. Li, N. Farzadnia, C. Shi, The role of seawater in interaction of slag and silica fume with cement in low water-to-binder ratio pastes at the early age of hydration, Construct. Build. Mater. 185 (2018) 508–518, https://doi.org/10.1016/j.conbuildmat.2018.07.091.
[43] J. Liu, R. An, Z. Jiang, H. Jin, J. Zhu, W. Liu, Z. Huang, F. Xing, J. Liu, X. Fan, T. Sui, Effects of w/b ratio, fly ash, limestone calcined clay, seawater and sea-sand on workability, mechanical properties, drying shrinkage behavior and micro-structural characteristics of concrete, Construct. Build. Mater. 321 (2022), https://doi.org/10.1016/j.conbuildmat.2022.126333.
[44] J. Liu, J. Liu, H. Jin, X. Fan, Z. Jiang, J. Zhu, W. Liu, Evaluation of the pore characteristics and microstructures of concrete with fly ash, limestone-calcined clay, seawater, and sea sand, Arabian J. Sci. Eng. 47 (2022) 13603–13622, https://doi.org/10.1007/s13369-022-06809-2.
[45] J.X. Lu, P. Shen, Y. Zhang, H. Zheng, Y. Sun, C.S. Poon, Early-age and microstructural properties of glass powder blended cement paste: improvement by seawater, Cem. Concr. Compos. 122 (2021), https://doi.org/10.1016/j.cemconcomp.2021.104165.
[46] P. Sikora, D. Lootens, M. Liard, D. Stephan, The effects of seawater and nanosilica on the performance of blended cements and composites, Appl. Nanosci. 10 (2020) 5009–5026, https://doi.org/10.1007/s13204-020-01328-8.
[47] A. Younis, U. Ebead, P. Suraneni, A. Nanni, Fresh and hardened properties of seawater-mixed concrete, Construct. Build. Mater. 190 (2018) 276–286, https://doi.org/10.1016/j.conbuildmat.2018.09.126.
[48] L.G. Li, X.Q. Chen, S.H. Chu, Y. Ouyang, A.K.H. Kwan, Seawater cement paste: effects of seawater and roles of water film thickness and superplasticizer dosage, Construct. Build. Mater. 229 (2019), https://doi.org/10.1016/j.conbuildmat.2019.116862.
[49] J. Ren, X. Wang, S. Xu, Q. Luo, Y. Fang, J. Zhu, F. Xing, Effects of polycarboxylate superplasticiser on hydration characteristics and hardened properties of cement blended with seawater, Construct. Build. Mater. 304 (2021), https://doi.org/10.1016/j.conbuildmat.2021.124660.
[50] J. Wang, J. Xie, Y. Wang, Y. Liu, Y. Ding, Rheological properties, compressive strength, hydration products and microstructure of seawater-mixed cement pastes, Cem. Concr. Compos. 114 (2020), https://doi.org/10.1016/j.cemconcomp.2020.103770.
[51] T. Alomayri, M.T. Amir, B. Ali, S.S. Raza, M. Hamad, Mechanical, tidal erosion, and drying shrinkage behaviour of high performance seawater concrete incorporating the high volume of GGBS and polypropylene fibre, J. Build. Eng. 76 (2023), 107377, https://doi.org/10.1016/j.jobe.2023.107377.
[52] M. Khatibmasjedi, S. Ramanathan, P. Suraneni, A. Nanni, Compressive strength development of seawater-mixed concrete subject to different curing regimes, ACI Mater. J. 117 (2020) 3–12, https://doi.org/10.14359/51725973.
[53] Q. Xie, J. Xiao, K. Zhang, Z. Zong, Compressive behavior and microstructure of concrete mixed with natural seawater and sea sand, Front. Struct. Civ. Eng. 15 (2021) 1347–1357, https://doi.org/10.1007/s11709-021-0780-2.
[54] A. Khazana, E. Assaly, POTIENTIAL INCORPORATION OF SALINE WATER INTO PORTLAND CEMENT REINFORCED CONCRETE, n.d..
[55] O. Şimşek, & H. Yılmaz Aruntaş, İ. Demir, H. Yaprak, S. Yazıcıoğlu, Investigation of the Effect of Seawater and Sulfate on the Properties of Cementitious Composites Containing Silica Fume, (n.d.). https://doi.org/10.1007/s12633-021-01052-0/Published. .
[56] A. Patil, A. Kumar Dwivedi, Mechanical strength and durability performance of sea water concrete incorporating supplementary cementitious materials in different curing conditions, Mater. Today Proc. 65 (2022) 969–974, https://doi.org/10.1016/j.matpr.2022.03.600.
[57] F. Adeyemi Olutoge, F. Adeyemi, G. Modupeola, The Effect of Sea Water on Compressive Strength of Concrete, 2014. www.ijesi.org.
[58] F.M. Wegian, Effect of seawater for mixing and curing on structural concrete, IES J. Part A Civ. Struct. Eng. 3 (2010) 235–243, https://doi.org/10.1080/19373260.2010.521048.
[59] H. Adnan, Parung, M.W. Tjaronge, R. Djamaluddin, Bond between steel reinforcement bars and seawater concrete, Civil Engineering Journal (Iran) 6 (2020) 61–68, https://doi.org/10.28991/cej-2020-SP(EMCE)-06.
[60] E. Bachtiar, M.W. Tjaronge, Microstructure characteristics of self compacting concrete using sea water, n.d. https://www.researchgate.net/publication/290087099..
[61] Q. Guo, L. Chen, H. Zhao, J. Admilson, W. Zhang, The effect of mixing and curing sea water on concrete strength at different ages, MATEC Web of Conferences 142 (2018), 02004, https://doi.org/10.1051/matecconf/201814202004.
[62] G. Chen, P. Liu, T. Jiang, Z. He, X. Wang, L. Lam, J.F. Chen, Effects of natural seawater and sea sand on the compressive behaviour of unconfined and carbon fibre-reinforced polymer-confined concrete, Adv. Struct. Eng. 23 (2020) 3102–3116, https://doi.org/10.1177/1369433220920459.
[63] X. Feng, L. Zhang, J. Zhang, X. Lu, Y. Xu, X. Zhang, R. Shi, D. Chen, Effect of Aluminum tri-polyphosphate on corrosion behavior of reinforcing steel in seawater prepared coral concrete, J. Wuhan Univ. Technol.-Materials Sci. Ed. 34 (2019) 906–913, https://doi.org/10.1007/s11595-019-2136-5.
[64] D. Permana Mansyur, Mechanical behaviour and microstructure characteristic of concrete by using freshwater and seawater, Civil Engineering Journal (Iran) 6 (2020) 1195–1203, https://doi.org/10.28991/cej-2020-03091540.
[65] J. Xiao, K. Zhang, Q. Zhang, Strain rate effect on compressive stress–strain curves of recycled aggregate concrete with seawater and sea sand, Construct. Build. Mater. 300 (2021), https://doi.org/10.1016/j.conbuildmat.2021.124014.
[66] T.U. Mohammed, H. Hamada, T. Yamaji, Performance of seawater-mixed concrete in the tidal environment, Cement Concr. Res. 34 (2004) 593–601, https://doi.org/10.1016/j.cemconres.2003.09.020.
[67] S. Yang, J. Xu, C. Zang, R. Li, Q. Yang, S. Sun, Mechanical properties of alkali-activated slag concrete mixed by seawater and sea sand, Construct. Build. Mater. 196 (2019) 395–410, https://doi.org/10.1016/j.conbuildmat.2018.11.113.
[68] A. Younis, U. Ebead, P. Suraneni, A. Nanni, Strength, shrinkage, and permeability performance of seawater concrete, in: ISEC 2019 - 10th International Structural Engineering and Construction Conference, 2019, pp. 1–6, https://doi.org/10.14455/isec.res.2019.159.
[69] M. Khatibmasjedi, S. Ramanthan, P. Suraneni, A. Nanni, Shrinkage behavior of cementitious mortars mixed with seawater, Adv Civ Eng Mater 8 (2019), https://doi.org/10.1520/ACEM20180110.
[70] A.M.T. Isam, O.O. Mahgoub, I.O. Haider, M.R. Tarig, H.S. Osman, B.A. Abdel-Hafiz, Influence of seawater in strengths of concrete mix design when used in mixing and curing, in: Key Eng Mater, Trans Tech Publications Ltd, 2016: pp. 382–389. https://doi.org/10.4028/www.scientific.net/KEM.711.382..
[71] A. Younis, U. Ebead, P. Suraneni, A. Nanni, Performance of seawater-mixed recycled-aggregate concrete, J. Mater. Civ. Eng. 32 (2020), https://doi.org/10.1061/(asce)mt.1943-5533.0002999.
[72] P.J. Nixon, C.L. Paget, R. Bollinghaus, Influence of sodium chloride on alkali-silica reaction, Adv. Cement Res. 1 (2) (1988) 99–106, https://doi.org/10.1680/adcr.1988.1.2.99.

[73] A. Shayan, A. Xu, G. Chirgwin, H. Morris, Effects of seawater on AAR expansion of concrete, Cement Concr. Res. 40 (2010) 563–568, https://doi.org/10.1016/j.cemconres.2009.09.008.
[74] H.M. Cai, W.U. Qing, L. Shen, Research on frost resistance of seawater sea-stone concrete, in: IOP Conf Ser Earth Environ Sci, Institute of Physics Publishing, 2019, https://doi.org/10.1088/1755-1315/267/5/052001.
[75] J. Liu, J. Liu, X. Fan, H. Jin, J. Zhu, Z. Huang, F. Xing, T. Sui, Experimental analysis on water penetration resistance and micro properties of concrete: effect of supplementary cementitious materials, seawater, sea-sand and water-binder ratio, J. Build. Eng. 50 (2022), https://doi.org/10.1016/j.jobe.2022.104153.
[76] O. Arasteh-Khoshbin, S.M. Seyedpour, T. Ricken, The effect of Caspian Sea water on mechanical properties and durability of concrete containing rice husk ash, nano SiO 2 , and nano Al 2O 3, Sci. Rep. 12 (2022), https://doi.org/10.1038/s41598-022-24304-4.
[77] T. Jena, K.C. Panda, Influence of sea water on strength and durability properties of concrete, ume Three, in: Advances in Structural Engineering: Materials, Springer India, 2015, pp. 1863–1873, https://doi.org/10.1007/978-81-322-2187-6_143.
[78] B. Da, Y. Li, H. Yu, H. Ma, H. Chen, X. Dou, Z. Wu, Effect of carbonation and drying-wetting cycles on chloride diffusion behavior of coral aggregate seawater concrete, J. Ocean Univ. China 21 (2022) 113–123, https://doi.org/10.1007/s11802-022-4847-z.
[79] N. Otsuki, T. Nishida, C. Yi, T. Nagata, H. Ohara, Effect of blast furnace slag powder and fly ash on durability of concrete mixed with seawater, in: Proceedings of the 4th International Conference on the Durability of Concrete Structures, ICDCS, 2014, pp. 229–241, https://doi.org/10.5703/1288284315406, 2014.
[80] Q. Li, H. Geng, Y. Huang, Z. Shui, Chloride resistance of concrete with metakaolin addition and seawater mixing: a comparative study, Construct. Build. Mater. 101 (2015) 184–192, https://doi.org/10.1016/j.conbuildmat.2015.10.076.
[81] M. Decker, R. Grosch, S. Keßler, H. Hilbig, Chloride migration measurement for chloride and sulfide contaminated concrete, Materials and Structures/Materiaux et Constructions 53 (2020), https://doi.org/10.1617/s11527-020-01526-4.
[82] S.K. Kaushik, S. Islam, Suitability of sea water for mixing structural concrete exposed to a marine environment, Cement Concr. Compos. 17 (1995) 177–185.
[83] A. Dasar, D. Patah, H. Hamada, Y. Sagawa, D. Yamamoto, Applicability of seawater as a mixing and curing agent in 4-year-old concrete, Construct. Build. Mater. 259 (2020), https://doi.org/10.1016/j.conbuildmat.2020.119692.
[84] C.L.C. Roxas, B.A. Lejano, Macrocell corrosion assessment of steel in cold-jointed concrete mixed and cured in seawater, Int. J. GEOMATE 14 (2018) 83–89, https://doi.org/10.21660/2018.42.7176.
[85] H. Hamada, N. Otsuki, T. Nishida, Seawater in Concrete Mix, CRC Press, 2021, https://doi.org/10.1201/9781003194163.
[86] B.A. Lejano, C.L.C. Roxas, Influence of seawater on the strength of RC beams and corrosion behavior of steel, Int. J. GEOMATE 14 (2018) 58–64, https://doi.org/10.21660/2018.42.7158.
[87] J. Zhou, Z. Ou, Q. Chen, Y. Chen, The Influence of Admixtures on the Corrosion Protection Afforded Steel Reinforcement in Seawater-And-Seasand Concrete, Adv Mat Res, 2011, pp. 81–89, https://doi.org/10.4028/www.scientific.net/AMR.250-253.81.
[88] G. Wang, Q. Wu, X.Z. Li, J. Xu, Y. Xu, W.H. Shi, S.L. Wang, Microscopic analysis of steel corrosion products in seawater and sea-sand concrete, Materials 12 (2019), https://doi.org/10.3390/ma12203330.
[89] P.S. Mangat, B.T. Molloyt, Chloride Binding in Concrete Containing PFA, Gbs or Silica Fume under Sea, Mag. Concr. Res. 47 (171) (1995) 129–141.
[90] Y. Zhao, X. Hu, Q. Yuan, Z. Wu, C. Shi, Effects of water to binder ratio on the chloride binding behaviour of artificial seawater cement paste blended with metakaolin and silica fume, Construct. Build. Mater. 353 (2022), https://doi.org/10.1016/j.conbuildmat.2022.129110.
[91] S. Cheng, Z. Shui, T. Sun, Y. Huang, K. Liu, Effects of seawater and supplementary cementitious materials on the durability and microstructure of lightweight aggregate concrete, Construct. Build. Mater. 190 (2018) 1081–1090, https://doi.org/10.1016/j.conbuildmat.2018.09.178.
[92] R. Liu, F. Jiang, Z. Liu, Research and Development Progress on Concrete Preparation with Seawater, Adv Mat Res, 2012, pp. 34–37, https://doi.org/10.4028/www.scientific.net/AMR.450-451.34.
[93] X. Liu, B. Ma, H. Tan, H. Li, J. Mei, T. Zhang, P. Chen, B. Gu, Chloride immobilization of cement-based material containing nano-Al2O3, Construct. Build. Mater. 220 (2019) 43–52, https://doi.org/10.1016/j.conbuildmat.2019.05.148.
[94] N. Tsuyuki, R. Watanabe, K. Koizumi, Y. Umemura, O. Machinaga, Effects of Barium Salt on the Fixation of Chloride Ions in Hardened Mortars, n.d..
[95] N. Zhu, F. Jin, X. Kong, Y. Xu, J. Zhou, B. Wang, H. Wu, Interface and anti-corrosion properties of sea-sand concrete with fumed silica, Construct. Build. Mater. 188 (2018) 1085–1091, https://doi.org/10.1016/j.conbuildmat.2018.08.040.
[96] S.K. Nguyen, A.T. Nguyen-Phung, H. Thai Le, T. Tri Ho, T.H. Nguyen-Ngoc, S. P. Yap, N. Chijiwa, N. Otsuki, Chloride binding ability and anti-corrosion properties of supersulfated cement in seawater and sand mixing concrete, Lecture Notes in Civil Engineering 8 (2018) 367–376.
[97] X. Wu, H. Huang, H. Liu, J. Hu, K. Wu, J. Wei, Q. Yu, A new self-healing agent for accelerating the healing kinetics while simultaneously binding seawater ions in cracked cement paste, Mater. Lett. 283 (2021), https://doi.org/10.1016/j.matlet.2020.128884.
[98] D.A. Koleva, An innovative approach to control steel reinforcement corrosion by self-healing, Materials 11 (2018), https://doi.org/10.3390/ma11020309.
[99] P. Krivenko, I. Rudenko, O. Konstantynovskyi, D. Vaičiukynienė, Mitigation of corrosion initiated by Cl− and SO42−-ions in blast furnace cement concrete mixed with sea water, Materials 15 (2022), https://doi.org/10.3390/ma15093003.
[100] X. Jiang, Z. Zhong, W. Liu, Influence of mineral admixture in CSA cement on chloride binding capacity, in: IOP Conf Ser Earth Environ Sci, Institute of Physics Publishing, 2019, https://doi.org/10.1088/1755-1315/283/1/012014.
[101] C. Pan, X. Li, J. Mao, The effect of a corrosion inhibitor on the rehabilitation of reinforced concrete containing sea sand and seawater, Materials 13 (2020), https://doi.org/10.3390/ma13061480.
[102] C. Xu, Z. Ou, J. Zhou, H. Chen, C. Qiao, Investigation on protectional ability on steel bar of compound corrosion inhibitor applied in seawater-and-sea sand concrete, in: Applied Mechanics and Materials, 2011, pp. 864–870, https://doi.org/10.4028/www.scientific.net/AMM.71-78.864.
[103] M.A. Asaad, M. Ismail, M.M. Tahir, G.F. Huseien, P.B. Raja, Y.P. Asmara, Enhanced corrosion resistance of reinforced concrete: role of emerging eco-friendly Elaeis guineensis/silver nanoparticles inhibitor, Construct. Build. Mater. 188 (2018) 555–568, https://doi.org/10.1016/j.conbuildmat.2018.08.140.
[104] X. Feng, Y. Zhang, X. Lu, Y. Xu, L. Zhang, C. Zhu, T. Wu, Y. Yang, X. Zhao, Corrosion performance of stainless steel reinforcement in the concrete prepared with seawater and coral waste and its ecological effects, J Renew Mater 8 (2020) 513–534, https://doi.org/10.32604/jrm.2020.09549.
[105] F. Lollini, M. Carsana, M. Gastaldi, E. Redaelli, L. Bertolini, A. Nanni, Preliminary assessment of durability of sustainable RC structures with mixed-in seawater and stainless steel reinforcement, in: Key Eng Mater, Trans Tech Publications Ltd, 2016, pp. 52–59, https://doi.org/10.4028/www.scientific.net/KEM.711.52.
[106] F. Lollini, M. Carsana, M. Gastaldi, E. Redaelli, Seawater and stainless steel bars for sustainable reinforced concrete structures, in: IOP Conf Ser Earth Environ Sci, Institute of Physics Publishing, 2019, https://doi.org/10.1088/1755-1315/296/1/012017.
[107] B. Shang, Y. Ma, M. Meng, Y. Li, Feasibility of utilizing 2304 duplex stainless steel rebar in seawater concrete: passivation and corrosion behavior of steel rebar in simulated concrete environments, Mater. Corros. 70 (2019) 1657–1666, https://doi.org/10.1002/maco.201910807.
[108] B. Shang, Y. Li, Application feasibility of HRB400 steel in seawater and marine sand concrete, Mater. Corros. 69 (2018) 1478–1488, https://doi.org/10.1002/maco.201810169.
[109] X. Yu, S. Al-saadi, I. Kohli, X.L. Zhao, R.K. Singh Raman, Austenitic stainless-steel reinforcement for seawater sea sand concrete: investigation of stress corrosion cracking, Metals 11 (2021) 1–10, https://doi.org/10.3390/met11030500.
[110] Y.Z. Mao, Y.H. Wei, H.T. Zhao, C.X. Lv, H.J. Cao, J. Li, Corrosion behavior of epoxy-coated rebar with pinhole defect in seawater concrete, Acta Metall. Sin. 31 (2018) 1171–1182, https://doi.org/10.1007/s40195-018-0755-z.
[111] L. Wan, Y. Wei, H. Zhao, H. Cao, J. Li, Influence of microdefect size on corrosion behavior of epoxy-coated rebar for application in seawater-mixed concrete, Coatings 11 (2021), https://doi.org/10.3390/coatings11040439.
[112] E. Redaelli, M. Carsana, F. Lollini, M. Gastaldi, F.T. Isfahani, Sustainable Concrete with Seawater and Corrosion Resistant Reinforcement: Results of Monitoring of Corrosion Behaviour, n.d..
[113] X. Guo, C. Xiong, Z. Jin, B. Pang, A review on mechanical properties of FRP bars subjected to seawater sea sand concrete environmental effects, J. Build. Eng. 58 (2022), https://doi.org/10.1016/j.jobe.2022.105038.
[114] M. Bazli, M. Heitzmann, B.V. Hernandez, Hybrid fibre reinforced polymer and seawater sea sand concrete structures: a systematic review on short-term and long-term structural performance, Construct. Build. Mater. 301 (2021), https://doi.org/10.1016/j.conbuildmat.2021.124335.
[115] G. Zheng, H. Cheng, H. Liang, Experimental Study on the Axial Compressive Properties of FRP-Reinforced Seawater Aggregate Concrete Brick Masonry, n.d..
[116] F. Ren, T. Liu, G. Chen, P. Xie, M.X. Xiong, T. Yuan, Y. Chen, S. Guo, Flexural behavior and modelling of FRP-bar reinforced seawater sea sand concrete beams exposed to subtropical coastal environment, Construct. Build. Mater. 309 (2021), https://doi.org/10.1016/j.conbuildmat.2021.125071.
[117] S. Fang, L. Li, Z. Luo, Z. Fang, D. Huang, F. Liu, H. Wang, Z. Xiong, Novel FRP interlocking multi-spiral reinforced-seawater sea-sand concrete square columns with longitudinal hybrid FRP–steel bars: Monotonic and cyclic axial compressive behaviours, Compos. Struct. 305 (2023), https://doi.org/10.1016/j.compstruct.2022.116487.
[118] B. Zhang, F. Li, H. Zhu, Z. Yang, Z. Dong, J. Chen, Basalt FRP-confined slag-based alkali-activated seawater coral aggregate concrete: concept and axial stress-strain behavior, Eng. Struct. 273 (2022), https://doi.org/10.1016/j.engstruct.2022.114890.
[119] Z. Chen, S. Li, J. Zhou, R. Xu, S. Dai, Flexural behavior of GFRP bars reinforced seawater sea sand concrete beams exposed to marine environment: experimental and numerical study, Construct. Build. Mater. 349 (2022), https://doi.org/10.1016/j.conbuildmat.2022.128784.
[120] X. Hu, J. Xiao, K. Zhang, Q. Zhang, The state-of-the-art study on durability of FRP reinforced concrete with seawater and sea sand, J. Build. Eng. 51 (2022), https://doi.org/10.1016/j.jobe.2022.104294.
[121] Z. Dong, G. Wu, Y. Xu, Experimental study on the bond durability between steel-FRP composite bars (SFCBs) and sea sand concrete in ocean environment, Construct. Build. Mater. 115 (2016) 277–284, https://doi.org/10.1016/j.conbuildmat.2016.04.052.
[122] A. Younis, U. Ebead, A. Nanni, A Perspective on Seawater/frp Reinforcement in Concrete Structures, ISEC 2017 - 9th International Structural Engineering and Construction Conference: Resilient Structures and Sustainable Construction, 2017, pp. 1–6, https://doi.org/10.14455/isec.res.2017.159.

[123] Z. Dong, G. Wu, X.L. Zhao, H. Zhu, Y. Wei, Z. Yan, Mechanical properties of discrete BFRP needles reinforced seawater sea-sand concrete-filled GFRP tubular stub columns, Construct. Build. Mater. 244 (2020), https://doi.org/10.1016/j.conbuildmat.2020.118330.
[124] Z. Dong, G. Wu, H. Zhu, X.L. Zhao, Y. Wei, H. Qian, Flexural behavior of seawater sea-sand coral concrete–UHPC composite beams reinforced with BFRP bars, Construct. Build. Mater. 265 (2020), https://doi.org/10.1016/j.conbuildmat.2020.120279.
[125] Y.L. Li, X.L. Zhao, R.K. Singh Raman, Mechanical properties of seawater and sea sand concrete-filled FRP tubes in artificial seawater, Construct. Build. Mater. 191 (2018) 977–993, https://doi.org/10.1016/j.conbuildmat.2018.10.059.
[126] Y. Wei, P. Xu, Y. Zhang, G. Wang, K. Zheng, Compressive behaviour of FRP-steel wire mesh composite tubes filled with seawater and sea sand concrete, Construct. Build. Mater. 314 (2022), https://doi.org/10.1016/j.conbuildmat.2021.125608.
[127] J.J. Zeng, W.Y. Gao, Z.J. Duan, Y.L. Bai, Y.C. Guo, L.J. Ouyang, Axial compressive behavior of polyethylene terephthalate/carbon FRP-confined seawater sea-sand concrete in circular columns, Construct. Build. Mater. 234 (2020), https://doi.org/10.1016/j.conbuildmat.2019.117383.
[128] G. Wang, Y. Wei, K. Miao, K. Zheng, F. Dong, Axial compressive behavior of seawater sea-sand coral aggregate concrete-filled circular FRP-steel composite tube columns, Construct. Build. Mater. 315 (2022), https://doi.org/10.1016/j.conbuildmat.2021.125737.
[129] J. Yang, J. Wang, Z. Wang, Axial compressive behavior of partially CFRP confined seawater sea-sand concrete in circular columns – Part I: experimental study, Compos. Struct. 246 (2020), https://doi.org/10.1016/j.compstruct.2020.112373.
[130] K. Zhang, Q. Zhang, J. Xiao, Durability of FRP bars and FRP bar reinforced seawater sea sand concrete structures in marine environments, Construct. Build. Mater. 350 (2022), https://doi.org/10.1016/j.conbuildmat.2022.128898.
[131] Z. Dong, G. Wu, X.L. Zhao, H. Zhu, J. Lian, Bond durability of steel-FRP composite bars embedded in seawater sea-sand concrete under constant bending and shearing stress, Construct. Build. Mater. 192 (2018) 808–817, https://doi.org/10.1016/j.conbuildmat.2018.10.154.
[132] A. Goyal, S.R. Karade, Efficiency of cathodic prevention to control corrosion in seawater mixed concrete, Journal of Building Pathology and Rehabilitation 5 (2020), https://doi.org/10.1007/s41024-020-00090-2.
[133] A. Goyal, H.S. Pouya, E. Ganjian, P. Claisse, A review of corrosion and protection of steel in concrete, Arabian J. Sci. Eng. 43 (2018) 5035–5055, https://doi.org/10.1007/s13369-018-3303-2.
[134] H.-S. Liang, J.-H. Zhu, F. Xing, Z.-W. Zeng, M.-N. Su, T. Ueda, L.-L. Wei, Experimental Investigation on the ICCP-SS Technique for Sea-Sand RC Beams, n.d..
[135] Y. Jiangtao, L. Keke, X. Qingfeng, L. Zhanhong, O. Lijun, Feasibility of using seawater to produce ultra-high ductile cementitious composite for construction without steel reinforcement, Struct. Concr. 20 (2019) 774–785, https://doi.org/10.1002/suco.201800116.
[136] B.T. Huang, Y.T. Wang, J.Q. Wu, J. Yu, J.G. Dai, C.K.Y. Leung, Effect of fiber content on mechanical performance and cracking characteristics of ultra-high-performance seawater sea-sand concrete (UHP-SSC), Adv. Struct. Eng. 24 (2021) 1182–1195, https://doi.org/10.1177/1369433220972452.
[137] C. Yue, H. Ma, H. Yu, J. Zhang, L. Chen, Q. Mei, Y. Tan, T. Liu, Experimental and three-dimensional Mesoscopic simulation study on coral aggregate seawater concrete with Dynamic Direct Tensile technology, Int. J. Impact Eng. 150 (2021), https://doi.org/10.1016/j.ijimpeng.2020.103776.
[138] H. Ma, C. Yue, H. Yu, Q. Mei, L. Chen, J. Zhang, Y. Zhang, X. Jiang, Experimental study and numerical simulation of impact compression mechanical properties of high strength coral aggregate seawater concrete, Int. J. Impact Eng. 137 (2020), https://doi.org/10.1016/j.ijimpeng.2019.103466.
[139] X. Sun, T. Li, F. Shi, X. Liu, Y. Zong, B. Hou, H. Tian, Sulphate corrosion mechanism of ultra-high-performance concrete (UHPC) prepared with seawater and sea sand, Polymers 14 (2022), https://doi.org/10.3390/polym14050971.
[140] W. Lun Lam, P. Shen, Y. Cai, Y. Sun, Y. Zhang, C. Sun Poon, Effects of seawater on UHPC: macro and microstructure properties, Construct. Build. Mater. 340 (2022), https://doi.org/10.1016/j.conbuildmat.2022.127767.
[141] X. Xue, F. Wang, J. Hua, N. Wang, L. Huang, Z. Chen, Y. Yao, Effects of polyoxymethylene fiber on fresh and hardened properties of seawater sea-sand concrete, Polymers 14 (2022), https://doi.org/10.3390/polym14224969.
[142] M.D. Jackson, G. Vola, D. Všianský, J.P. Oleson, B.E. Scheetz, C. Brandon, R. L. Hohlfelder, Cement microstructures and durability in Ancient Roman seawater concretes, RILEM Bookseries 7 (2013) 50–76, https://doi.org/10.1007/978-94-007-4635-0_5.
[143] C. Stanislao, C. Rispoli, G. Vola, P. Cappelletti, V. Morra, M. De Gennaro, Contribution to the knowledge of ancient Roman seawater concretes: phlegrean pozzolan adopted in the construction of the harbour at Soli-Pompeiopolis (Mersin, Turkey), Period. Mineral. 80 (2011) 471–488, https://doi.org/10.2451/2011PM0031.
[144] M.D. Jackson, S.R. Chae, S.R. Mulcahy, C. Meral, R. Taylor, P. Li, A.H. Emwas, J. Moon, S. Yoon, G. Vola, H.R. Wenk, P.J.M. Monteiro, Unlocking the secrets of Al-tobermorite in Roman seawater concrete, Am. Mineral. 98 (2013) 1669–1687, https://doi.org/10.2138/am.2013.4484.
[145] G. Vola, E. Gotti, C. Brandon, J.P. Oleson, R.L. Hohlfelder, Chemical, mineralogical and petrographic characterization of Roman ancient hydraulic concretes cores from Santa Liberata, Italy, and Caesarea Palestinae, Israel, Period. Mineral. 80 (2011) 317–338, https://doi.org/10.2451/2011PM0023.
[146] J. Elsen, O. Cizer, R. Snellings, Highlights and Breakthroughs Lessons from a lost technology: the secrets of Roman concrete, Am. Mineral. 98 (2013) 1917–1918, https://doi.org/10.2138/am.2013.4643.
[147] W. Ashraf, I.B. Borno, R.I. Khan, S. Siddique, M.I. Haque, A. Tahsin, Mimicking the cementation mechanism of ancient Roman seawater concrete using calcined clays, Appl. Clay Sci. 230 (2022), https://doi.org/10.1016/j.clay.2022.106696.
[148] P. Li, W. Li, K. Wang, H. Zhao, S.P. Shah, Hydration and microstructure of cement paste mixed with seawater – an advanced investigation by SEM-EDS method, Construct. Build. Mater. 392 (2023), https://doi.org/10.1016/j.conbuildmat.2023.131925.
[149] E. Redaelli, A. Arrigoni, M. Carsana, G. Dotelli, M. Gastaldi, F. Lollini, F. Bertola, F. Canonico, A. Nanni, Culvert prototype made with seawater concrete: materials characterization, monitoring, and environmental impact, Adv Civ Eng Mater 8 (2019), https://doi.org/10.1520/ACEM20180114.
[150] S. Dong, C. Li, G. Xian, Environmental impacts of glass-and carbon-fiber-reinforced polymer bar-reinforced seawater and sea sand concrete beams used in marine environments: an lca case study, Polymers 13 (2021) 1–16, https://doi.org/10.3390/polym13010154.
[151] V. Arosio, A. Arrigoni, G. Dotelli, Reducing water footprint of building sector: concrete with seawater and marine aggregates, in: IOP Conf Ser Earth Environ Sci, Institute of Physics Publishing, 2019, https://doi.org/10.1088/1755-1315/323/1/012127.