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Seawater concrete: A critical review and future prospects

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ABSTRACT

Concrete production requires a large amount of water which causes a shortage of natural freshwater. Conversely, seawater in concrete can improve sustainability in construction by reducing the excessive consumption of natural freshwater. In the literature, the use of seawater in concrete still has a controversial reputation. It is, therefore, crucial to understand the properties of concrete mixed and cured with seawater. The past and recent research on seawater concrete is thoroughly reviewed in this paper and identifies the significant differences in characteristics between seawater concrete and conventional concrete. Existing studies indicate that high chlorides in seawater enhance the hydration rate, shorten the setting time and increase the early strength of concrete. In order to lessen the effect of chlorides and increase the durability of seawater concrete, mineral admixtures, retarders, and superplasticizers have been recommended. Past studies have also revealed that the use of seawater in concrete will inevitably corrode steel bars. This article covers the advantages and disadvantages of adopting FRP and stainless steel bars to prevent the corrosion of steel reinforcement caused by seawater. It also suggests future possibilities of using natural and recycled aluminum reinforcement in seawater concrete which not only protects concrete from corrosion but also leads to the sustainability of concrete. Overall, the outcomes of this study will contribute to further research aimed at improving the properties of seawater concrete.

1. Introduction

1.1. Water crises

Concrete is a material that is used extensively on earth after water. As per the statistics provided by the Global Cement and Concrete Association, an estimated 14 billion cubic meters of concrete is produced annually (Malsang, 2021). However, the growing demand for concrete is increasing the consumption of natural materials needed for the preparation of concrete. The lack of these materials and continuous development in the infrastructure have resulted in a 4.5% increase in global construction costs and 23.1% rise in material costs in 2021. It is anticipated that construction costs will experience an additional 4 — 7% increase in 2022 (Murray, 2021). In addition, if the excessive use of natural materials is not controlled, it will deplete non-renewable resources (Ismail et al., 2013). Hence it is necessary to search for alternate materials to balance the rapidly growing demand for the construction industry and natural resource availability. The environment is also severely affected due to excessive consumption of natural materials. Many initiatives are taken worldwide to promote sustainability in construction to enhance the quality of residents' life while minimizing the impacts on the environment. To deal with this problem, many studies have been conducted which promote the use of industrial by-products or recycled materials in concrete to conserve the natural coarse and fine aggregates. On the contrary, little research is devoted to preserving natural freshwater, which is widely used for mixing and curing concrete.

Water is the chief ingredient for the concrete mix proportion and also the most vital need for life. Generally, freshwater is used for mixing and curing concrete, which is a limited resource. According to a report by the Economist Intelligence Unit, the acceleration of urbanization, population expansion, the impacts of climate change, and economic advancement are collectively exerting stress on water systems (Armstrong, 2023). The UN World Water Development Report 2022 states that industry and energy account for 19% of global freshwater withdrawals, including groundwater (UN Water, 2022; Krist and Payne, 2022). A high-water demand (nearly 75%) for concrete preparation may occur in 2050 in the areas where water scarcity is going to be a significant issue (Miller et al., 2018). Further, it was also reported that around 100 m^3 of water per day is used by a batching plant only for mixing concrete (Mack et al., 2015). If the same conventional concrete preparation process is used for the upcoming 35 years, approximately 590–710 km^3 of water will be consumed for concrete preparation only (Fry, 2006). As per the

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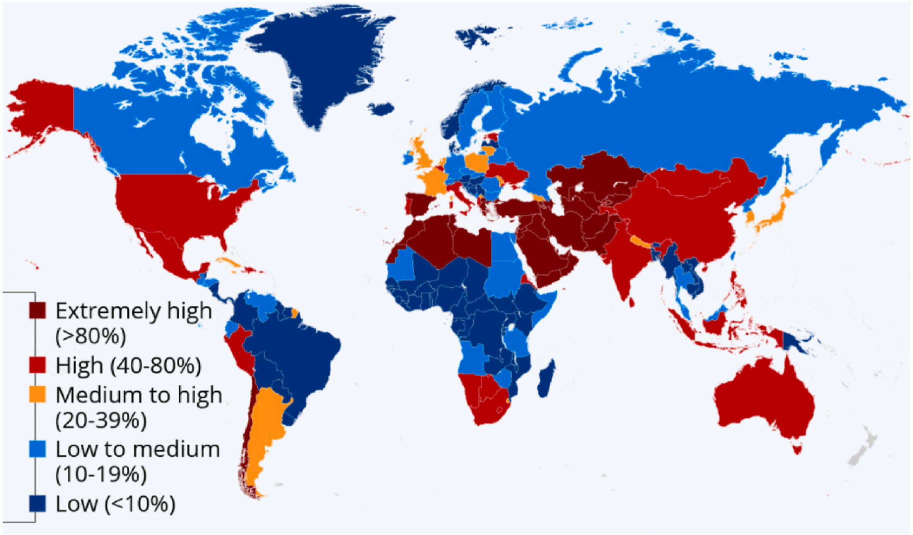

Fig. 1. Water-stressed countries in 2040 (Armstrong, 2023).

Table 1

Average salt concentration in different seas (Imre, 2011).

Sea	Dead Sea	Mediterranean	Indian Sea	North Sea and Atlantic	Black Sea	Baltic
Salts	5.3 %	3.8 %	3.55 %	3.5 %	1.8 %	0.7 %

United-Nations (2019), freshwater availability has become a challenge for more than 40% of the world's population. There is a double increase in water usage than in the previous century's population. According to the Aqueduct Water Risk Atlas by WRI about half of the global population, or 4 billion people, experience severe water stress for at least a month annually due to improper, inefficient and unsustainable usage of water (Kuzma et al., 2023). According to Armstrong (2023), 44 nations are expected to confront either extremely high or high water stress levels by 2040 (Fig. 1). The anticipated global water requirements are expected to rise between 20% and 25% by the year 2050 (Kuzma et al., 2023). This problem is becoming more complicated due to the infrastructure development, which is demanding more quantity of concrete and ultimately pressurizing the natural water resources. Therefore, the use of alternative sources for natural freshwater turns out to be essential for concreting. The earth's surface comprises approximately 71% of water, out of which 96.5% is seawater and the remaining 3.5% is freshwater, where only 0.8% or less is available for drinking purposes (Howard et al., 2019). Focusing on this, using seawater instead of freshwater for concreting can potentially conserve freshwater resources for future generations and maintain sustainability.

1.2. *Seawater*

Seawater is a complicated combination of several salts, including organisms, dissolved gases, suspended sediments, and organic matter. Seawater has a typical salt concentration of around 3.5%. However, it also depends on the geographic location of different seas, as shown in Table 1 (Imre, 2011). The pH estimation of seawater is somewhere in the range of 7.5 and 8.4, and the average value when it balances with CO_2 in the atmosphere is 8.2. (Mehta and Monteiro, 2001). Moreover, the composition of seawater salts can bring favorable or unfavorable effects on the properties of concrete blended with seawater. As per ASTM D1141-98 (2013) (ASTM, 2013), the different proportions of salts listed in Table 2 are required to represent seawater. Most studies followed the guidelines of ASTM D1141-98 (2013) (ASTM, 2013) for preparing artificial seawater to determine its effects on concrete properties. However, some studies were also found to utilize natural seawater. Table 3 presents the concentrations of various ions present in natural seawater. The first production of concrete using seawater can be

Table 2

Concentration of salts present in seawater (ASTM, 2013).

Chemicals	NaCl	$MgCl_2$	Na_2SO_4	$CaCl_2$	KCl	$NaHCO_3$	KBr
Concentration (g/L)	24.53	5.20	4.09	1.16	0.695	0.201	0.101

Table 3

Chemical composition of natural seawater.

Conc. of ions (mg/l)	Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}	CO_3^{2-}	S
Li et al. (2019)	21700	417	579	1040	33400	–	–	3840
Guo et al. (2020)	227.5	277.5	7220	687.5	10600	1080	28.63	–
Younis et al. (2018)	–	–	–	–	18600	2359	–	–
Wang et al. (2018)	15000	520	500	2300	26000	3700	–	–
Dasar et al. (2020)	9900	350	360	1200	18720	2370	–	–
Jiangtao et al. (2018)	11750	335.0	330.7	1157.8	14818.1	2489	–	–
Khatibmasjedi et al. (2019)	9585	329	389	1323	18759	–	–	–
Mohammed et al. (2004)	9290	346	356	1167	17087	2378	110	–
Adiwijaya et al. (2015)	9900	350	360	1200	18720	2370	–	–
Teng et al. (2019)	10419.4	354.4	358.2	1215.2	18152.6	1675.0	–	–

Table 4
Recommendations of various codes for mixing water in concrete.

Codes	Max. chloride content of mixing water (mg/l)	Max. sulfate content of mixing water (mg/l)	Recommendations for using seawater
BIS-456 (2000)	Plain concrete: 2000 Reinforced concrete: 500	400 as SO_3	Seawater could be used to mix or cure plain concrete if circumstances cannot be avoided.
BS-EN-1008 (2002)	Plain concrete: 4500 Reinforced concrete: 1000 Prestressed concrete: 500	2000 as SO_4^{2-}	If reinforcement is not used in concrete, seawater may be used for the preparation of concrete but should not be used in prestressed concrete.
ASTM-C1602 (2012)	Prestressed concrete: 500 Reinforced concrete: 100	3000 as SO_4	–

reported during the Second World War when seawater was utilized in concrete mixing to build structures nearby the coastal areas of California and Florida (Kaushik and Islam, 1995). However, few studies have shown that the ancient Romans were the first to use seawater to prepare concrete by utilizing natural mineral admixtures (Witze, 2017). The requirement of seawater for concrete mixing emerges in such conditions when freshwater is inaccessible or expensive to transport. Further, seawater's chlorides and sulfates are harmful to the durability of traditional steel reinforced concrete and their amount should be determined before use in concrete. Therefore, various codes have provided recommendations for using seawater, and threshold values of chlorides and sulfates in concrete mixing water are presented in Table 4.

The different salts present in seawater chemically react with concrete ingredients and change their properties. This article provides a critical review of existing research on the impact of seawater on various concrete properties. This study sums up the current knowledge of fresh properties, mechanical properties, and durability of concrete mixed and cured with seawater. Also, the research gap is identified and assigned by comparing results published in various publications. Moreover, this study also highlights the corrosion problem of steel bars due to seawater in concrete. In order to mitigate the corrosion problem, most existing studies utilize FRP and stainless steel reinforcement. Several drawbacks associated with these reinforcements are addressed in this paper before they could be used as reinforcement in seawater concrete. Due to non-corrosive and plastic behavior, aluminum alloy bars would also be used as reinforcing material in seawater concrete, but very limited research has been conducted in this field. This study proposes future possibilities for using recycled aluminum alloy bars in seawater concrete. Based on the review, the use of various mineral admixtures are also recommended to obtain a more sustainable and durable seawater concrete in the future. Hence, this paper summarizes the current understanding of seawater concrete performance, laying a solid foundation for further research in this field so that seawater can be widely used in plain and reinforced concrete.

2. Performance of plain concrete with seawater

It is usually considered that structural concrete should not be prepared by using seawater. However, the available literature breaks the myth of not using seawater in construction practices. The previous and current studies state that seawater does not affect the properties of plain concrete substantially. However, there are changes in plain concrete properties in fresh and hardened states due to the use of seawater which is described in the subsequent sections.

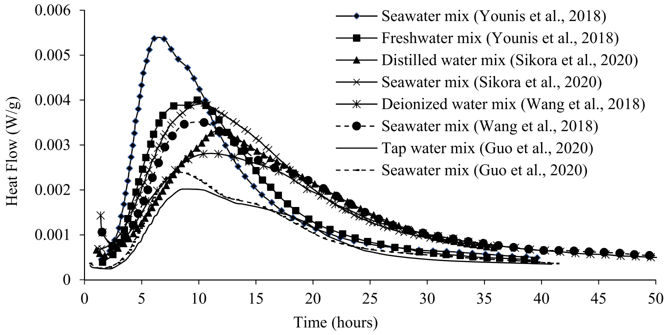

Fig. 2. Effect of seawater and freshwater on heat flow of cement.

2.1. Hydration rate

Seawater concrete and ordinary concrete exhibit different heat flow dynamics. As cement hydrates with seawater, its exotherm changes greatly, particularly at the beginning of the process. In accordance with existing literature, it has been proposed that seawater accelerates cement hydration by enhancing the hydration kinetics due to the presence of ample amounts of chlorides (Ebead et al., 2022; P. P. Li et al., 2021; Montanari et al., 2019). Younis et al. (2018) found an accelerated hydration reaction of cement when mixed with seawater. The maximum heat flow of cement paste with seawater was estimated at around 25% higher than the cement paste with freshwater. Also, the peak of cement paste with seawater had higher values (magnitude) and appeared first than freshwater cement paste. According to Sikora et al. (2020), the use of seawater in place of distilled water increases the hydration rate of cement, and the peak of heat flow reached 100 min earlier than the peak of cement paste with distilled water. The peak value of seawater cement paste was approximately 19% higher than the peak of distilled water cement paste. The reason behind the early hydration of cement with seawater was found as the presence of chloride ions (NaCl, $MgCl_2$ and $CaCl_2$) in seawater, which results in accelerated hydration reaction of cement and causes earlier production of C–S–H gel. Guo et al. (2020) also explored the higher heat flow values of seawater sea sand concrete than traditional concrete made with tap water. Furthermore, seawater was found to cause rapid and intense hydration of cement with a great quantity of heat generated. In addition, the study conducted by Wang et al. (2018) pointed out that seawater cement paste started to increase the heat flow peak between 1 and 10 h. Also, seawater cement paste produced 1.12 times more heat as compared to deionized water cement paste over a period of 72 h. It was also reported that seawater enhances the cement hydration rate more than a NaCl solution with same chloride concentration. This indicates that NaCl alone does not accelerates cement hydration as much as multiple seawater components (W. W. Li et al., 2021). The heat flow of cement due to seawater and freshwater from the above studies is compared in Fig. 2. The reasons behind increasing the hydration rate of cement due to the presence of chloride ions in seawater are explained as follows.

- The accelerated hydration could be described by the diffusion of chloride ions into the initial hydration products due to the comparatively smaller chloride ions than hydroxyl ions. These initial hydration products act as a passivating layer on the cement particles' surface. However, chloride ions will weaken or destroy this passivating layer when reacting with water, enhance dissolution of hydration products (as tri-calcium silicate) and increase hydration rate of cement (Li et al., 2018).
- Besides, the particles of cement have a mixture of negative and positive ions. So, the flocculation of cement particles takes place when they come in contact with water. On the other hand, chlorides are negatively charged (anions). Therefore, when chlorides get into the concrete through seawater, these anions are absorbed on the

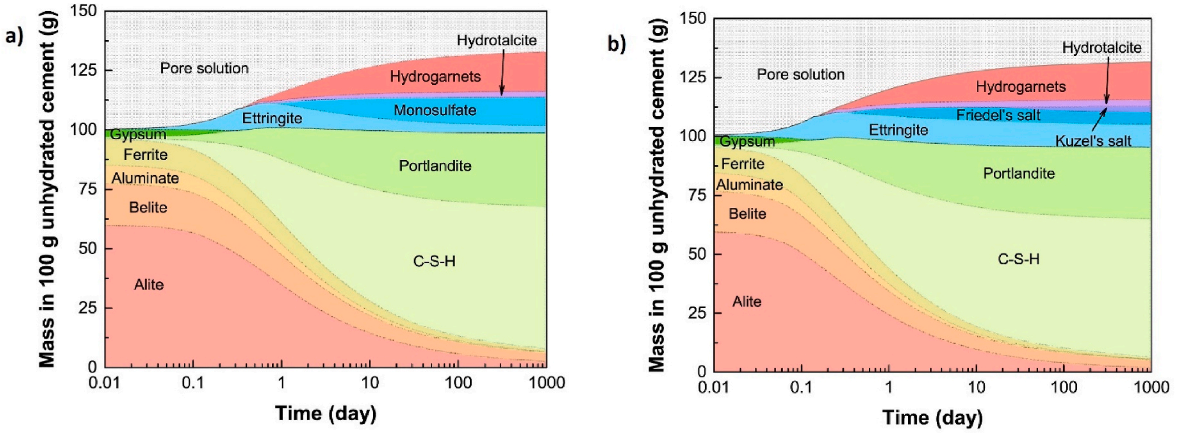

Fig. 3. The simulated phase evolution of Portland cement during the hydration in a) Deionized water, b) seawater (Li et al., 2023).

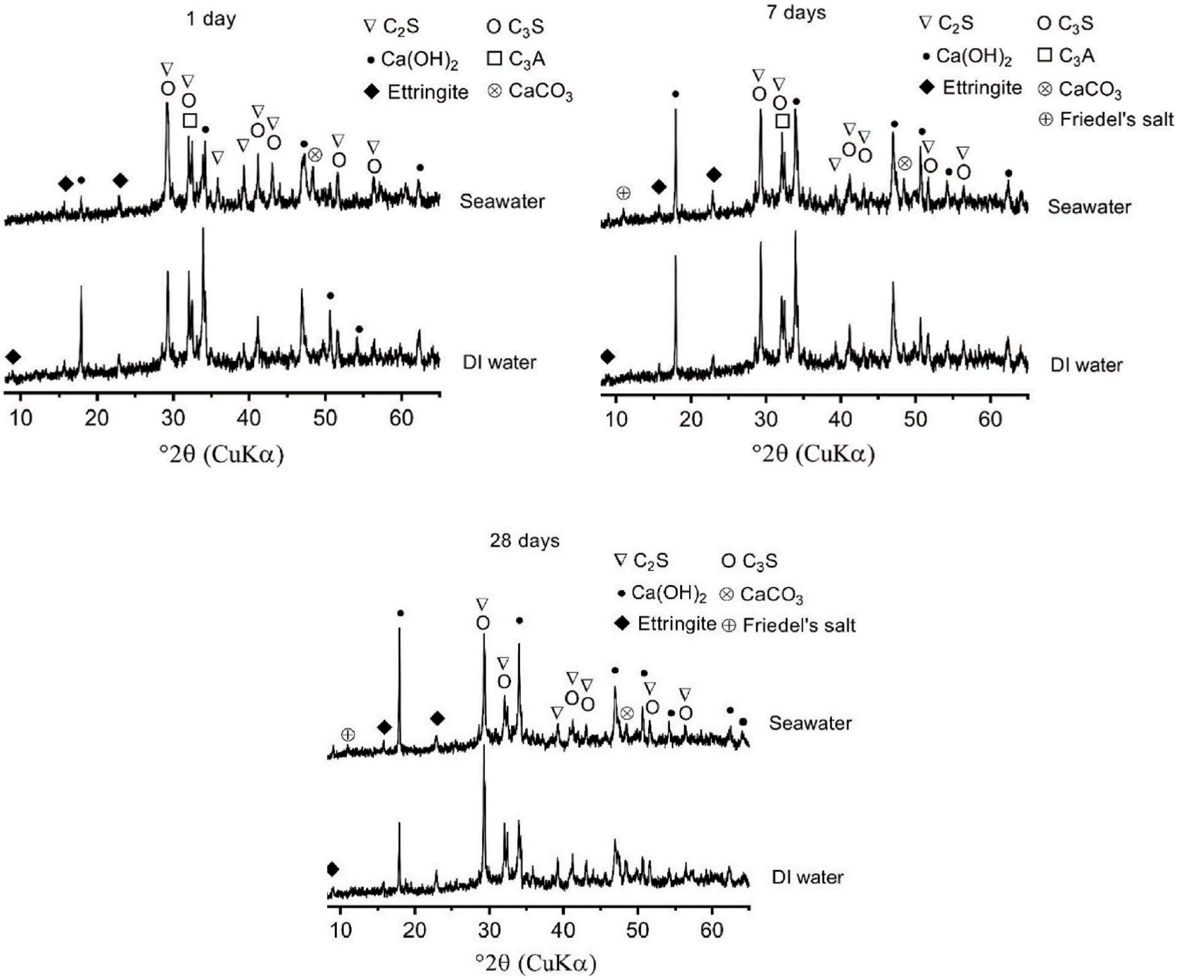

Fig. 4. Portland cement XRD with seawater and deionized water at 1, 7 and 28 days (Wang et al., 2018).

surface of the cement particles, causing them to become negatively charged. This phenomenon leads to the deflocculation and dispersion of cement particles and increases cement hydration (Lu et al., 2018).

- Furthermore, the salt NaCl in seawater can react with $Ca(OH)_2$ present in concrete and produce calcium chloride ($CaCl_2$) in the concrete (Eq. (1)) (Islam et al., 2005; Li et al., 2018; Shaikh and Dobson, 2019; Younis et al., 2018). Calcium chloride works as a catalyst for cement in the initial hydration period and catalysis the hydration of C_3S and C_2S. It probably leads to forming a porous C–S–H gel (calcium silicate hydrate). The porous structure of the C–S–H gel allows a quicker diffusion of ions, leading to rapid cement hydration (Bentz et al., 2016).

$$Ca(OH)_2 + 2NaCl \rightarrow CaCl_2 + 2Na^+ + 2OH^- \tag{1}$$

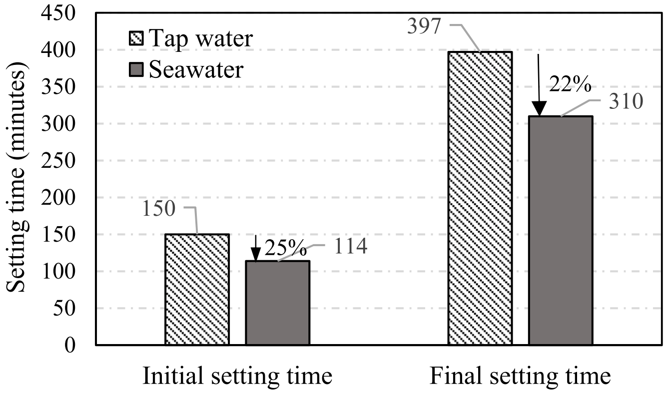

Fig. 5. Setting times of OPC with tap water and seawater (Y.Ghorab et al., 1990).

2.2. Hydration product

A typical hydration product Friedel's salt (FS) is produced by the reaction of chlorides of seawater with calcium-aluminate hydrates and calcium hydroxide in cement paste as shown in Eq. (2). Moreover, Kuzel's salt (KS), is also a hydration product of reaction between chloride and AFm, as illustrated in Eq. (3). KS exhibits a crystal structure resulting from the intercalation of FS and AFm. In environments with low chloride levels, FS can undergo a partial conversion to KS. It was found that FS and KS do not have a harmful effect on Portland cement. FS leads to enhance the hydration process of aluminate (C_3A) and ferrite (C_4AF) which could be helpful in binding more chlorides. Furthermore, the formation of FS precipitates plays a role in compacting pore structures, resulting in reduced permeability (Ting and Yi, 2023). Fig. 3 shows hydrated assemblage in Portland cement mixed and cured in deionized water and seawater (Li et al., 2023). Moreover, Fig. 4 presents data from X-ray Diffraction (XRD) of cement paste mixed and cured with seawater and deionized water, which shows distinct hydration compounds in cement paste mixed with seawater compared to deionized water and how these compounds change over time. FS is not present in cement paste that has been aged for one day in seawater; however, it becomes significantly evident after 7 and 28 days in seawater cement paste. Moreover, it's worth noting that portlandite seems to be present in smaller quantities in seawater cement specimens after one day of curing. However, at 7 and 28 days, the $CaCO_3$ content in seawater cement paste decreases. This could be due to some of the $CaCO_3$ reacts with C_3A or monosulfoaluminate and forms calcium carboaluminate. Additionally, the peaks of ettringite in seawater cement paste are more pronounced than in deionized water cement paste (Wang et al., 2018).

$$3CaO\cdot Al_2O_3\cdot 6H_2O + Ca(OH)_2 + 2Cl^- + 4H_2O \rightarrow 3CaO\cdot Al_2O_3\cdot CaCl_2\cdot 10H_2O\ (FS) + 2OH^- \tag{2}$$

$$3CaO\cdot Al_2O_3\cdot 6H_2O + 0.5Ca(OH)_2 + 0.5CaSO_4 + Cl^- + 4H_2O \rightarrow 3CaO\cdot Al_2O_3\cdot 0.5CaCl_2\cdot 0.5CaSO_4\cdot 10H_2O\ (KS) + OH^- \tag{3}$$

2.3. Setting time

The initial and final setting times of concrete are significantly affected by seawater when used to mix concrete. It is reported that seawater tends to decrease the setting time. As discussed earlier, the presence of chlorides in certain salts of seawater leads to speed up the hydration reaction and thereby decreases the setting time of concrete. The initial setting time is found to be more affected by the presence of seawater as compared to the final setting time (Ghorab et al., 1989). In the 1990s, in the study of Zhang et al. (1993), seawater from Qingdao China Sea was utilized for mixing concrete and found 45 min reduction in the initial and final setting times of cement paste as compared to freshwater cement paste. The study of Y.Ghorab et al. (1990) revealed that the initial and final setting times of OPC (Ordinary Portland Cement) were minimized to 25% and 22%, respectively when OPC was mixed and cured in seawater as compared to the OPC which was mixed and cured in tap water (Fig. 5). In recent studies, Katano et al. (2013) also observed that seawater concrete exhibited 90 and 135 min lesser initial and final setting times than conventional concrete. The study of Younis et al. (2018) explored that the use of seawater reduced the initial setting time of the fresh concrete by approximately 30%, whereas the use of seawater with recycled coarse aggregate decreased the initial setting time by about 50% as compared to ordinary concrete (Younis et al., 2020). Also, (Wang et al., 2023) observed a 27.9% reduction in the initial setting time and a 24.2% decrease in the final setting time of concrete when seawater was used. Such concrete could be used where the rapid concrete setting is required or setting time could be reduced by using retarders. However, the use of retarders in terms of the long-term performance of seawater concrete needs more research.

2.4. Workability

The use of seawater shows a reduction in the workability of concrete due to the acceleration in hydration reaction and seawater concrete was found to be more cohesive and compact and viscous than ordinary concrete. The presence of calcium chloride in seawater accelerates the C–S–H production and the heat generated in cement hydration drops the slump of seawater concrete sooner than freshwater concrete (Razak et al., 2023; Teng et al., 2019; Lyu et al., 2022) also noticed a decrement in the slump of geopolymer concrete with seawater. Younis et al. (2018) measured the 20% reduction in the initial slump flow of concrete made with seawater compared to the concrete prepared with freshwater. It was also investigated that tap water concrete achieved 625 mm slump flow, whereas seawater concrete 421 mm. The reduction in the slump was possibly due to the accelerated hydration process in the presence of seawater chlorides. Also, there was no separation and sufficient

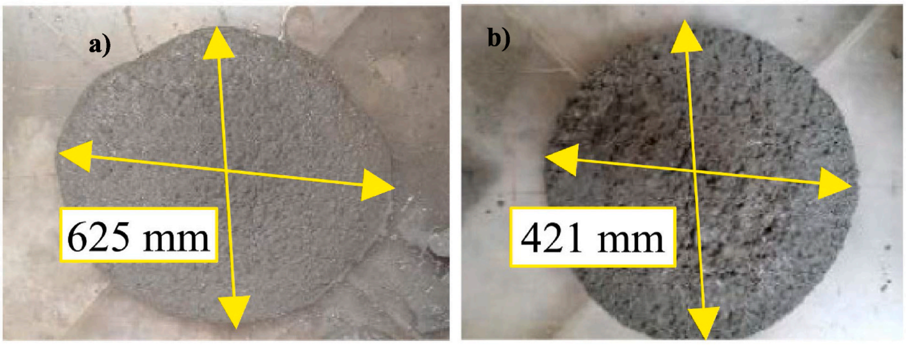

Fig. 6. Slump flow of concrete mixed with a) tap water and b) seawater (Soares et al., 2020).

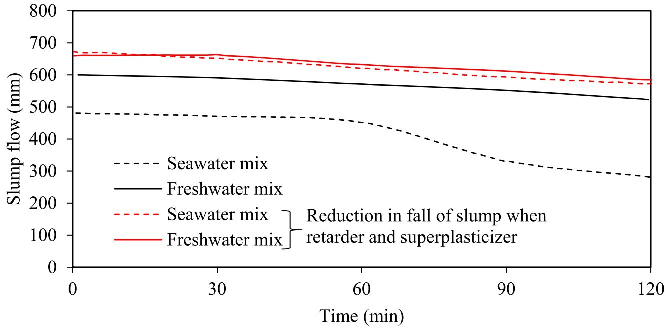

Fig. 7. Slump flow of concrete mixed with seawater and freshwater with time (Younis et al., 2018).

uniformity in the concrete mixed with seawater, as depicted in Fig. 6 (Soares et al., 2020). Li et al. (2019) conducted a study for comparing the workability of cement paste prepared with seawater and freshwater for different plasticizer doses and w/c ratios and found that the workability of the cement paste with both kinds of water varies in similar ways for different superplasticizer dosage and w/c ratios. However, a slight reduction in the slump of seawater paste was found as compared to freshwater paste, which could be caused by the early hydration of cement by seawater and the higher viscosity of seawater due to the presence of more amounts of suspended solids in seawater. Alomayri et al. (2023) & Liu et al. (2022) also observed a decrease in the slump of fresh concrete when seawater was substituted for freshwater. Furthermore, it was also explored that concrete prepared with seawater and recycled coarse aggregate remained flowable for 60 min, whereas conventional concrete remained flowable for 120 min (Younis et al., 2020). However, the fall in the slump was controlled by providing a sufficient dosage of retarders and superplasticizers, as shown in Fig. 7 (Younis et al., 2018).

2.5. *Strength*

Early research on seawater in concrete showed that seawater did not harm plain concrete performance. The problem in concrete prepared with seawater rises chiefly because of the rusting of steel bars. The study conducted by Griffin and Henry (1962) revealed that plain concrete properties did not get worsen by using seawater and there was no decrement in the strength of concrete by using seawater. In addition, seawater is responsible for the higher early strength of concrete but leads to reduce the long-term strength of concrete. The study of Kaushik and Islam (1995) claimed that seawater enhanced the initial strength of cement mortar for up to seven days, and then at 28 days, there was a drop of around 13% in the strength of seawater cement mortar as compared to tap water cement mortar. Mori (1981) underlined that after ten years, the strengths of concrete prepared with seawater and freshwater are almost the same. Besides, according to Taylor and Kuwairi (1978), as the water salinity increases, concrete strength also increases.

In recent times, Zhang et al. (2022) found that seawater cement paste exhibited higher compressive strength than deionized water cement paste after one day of curing but experienced a decline in strength after seven days of curing. Wegian (2010) also investigated that seawater concrete gained more compressive, flexural and tensile strengths at initial curing ages of 7 and 14 days as compared to concrete prepared and cured in freshwater whereas at later ages such as 90 days the strengths of seawater concrete reduced by 3.8–14.5% than that of freshwater concrete. A slight improvement in early strength (7 days age) of concrete mixed in seawater was observed by Younis et al. (2018), but the same concrete strength fell by 7–10% at 28 days. Likewise, Soares et al. (2020) achieved seven days compressive strength of concrete as 54.5 MPa by using seawater and a slightly lesser compressive strength (50.5 MPa) by using tap water while at 28 days. Patah et al. (2023) explores the enhanced compressive strength in concrete through the use of seawater for mixing and freshwater for curing when combined with fly ash and a water-to-binder ratio of 0.4. The combined use of seawater and sea sand is also found to increase the seven days compressive strength of concrete by 36–76%, but 28 days strength is approximately the same, and strength at 180 days is 3.7–10.2% lower when compared with freshwater concrete (Xiao et al., 2019). Similarly, the research of Guo et al. (2020) concluded that concrete prepared using seawater and sea sand showed around a 2–7% reduction in compressive strength at 28 days and a 10–13% reduction at 56 days when compared with traditional concrete.

Pan et al. (2021) also observed a 12.3% increment in compressive strength of seawater and sea sand concrete at 3 days, but the compressive strength of the same concrete decreased by 1.9% and 7.6% at 7 and 28 days, respectively. On the other hand, some studies also showed the increment in compressive strength of concrete up to 28 days and reduction at a later age due to the use of seawater for mixing (Goyal and Karade, 2020; Lollini et al., 2019; Wang et al., 2018). Sikora et al. (2019) reported a significant improvement in the compressive strength of cement paste for up to 14 days and also a little strength enhancement at 28 days using seawater than that of conventional cement pastes by using optimal levels of colloidal silica. Excessive or less use of colloidal silica nullifies its effects, emphasizing the importance of precise silica incorporation. Fig. 8 compares selected results from different studies of compressive strength of concrete prepared with seawater and freshwater (Goyal and Karade, 2020; Kaushik and Islam, 1995; Park et al., 2010; Younis et al., 2017, 2018). According to the literature, the improvement in the strength of concrete prepared with seawater at initial days could be due to the presence of NaCl in seawater, which speeds up the dissolution of tricalcium silicate and accelerates the hydration reaction

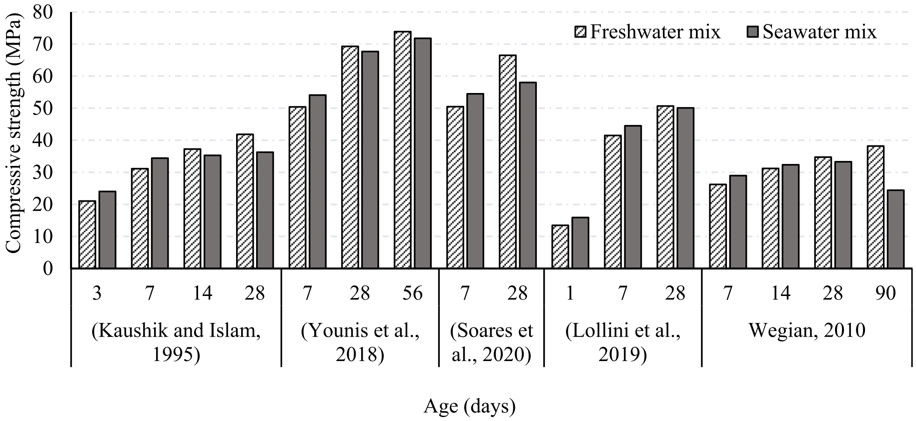

Fig. 8. Effect of seawater and freshwater on compressive strength.

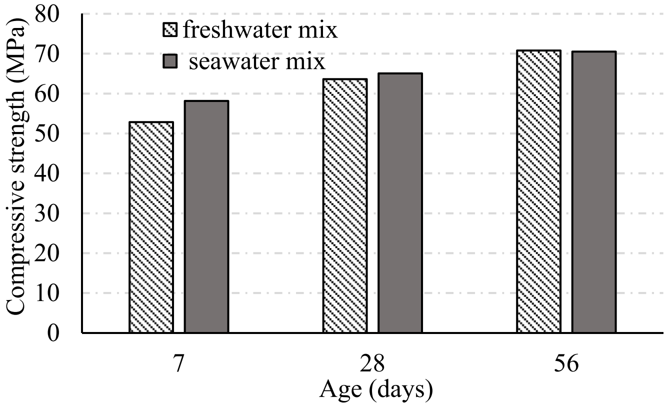

Fig. 9. Compressive strength of seawater concrete after remediation (Younis et al., 2018).

(Goyal and Karade, 2020; Soares et al., 2020; Xiao et al., 2019). This acceleration produces more hydration products, which fill the pores of the concrete and modify the microstructure (Kaushik and Islam, 1995; Wang et al., 2018). The reduction in long-term compressive strength in seawater concrete may be attributed to the presence of magnesium sulfate in seawater. This compound reacts with calcium hydroxide, resulting in the formation of expansive products that exert pressure on the surrounding concrete, consequently leading to the development of micro-cracks and a subsequent reduction in the concrete's later strength (Islam et al., 2005; Wegian, 2010; Xiao et al., 2019), (Please see section 2.6 for more details about the effects of sulfate on concrete). Also, Kaushik and Islam (1995) pointed out that the cement mortar made with seawater began to leach out soft hydration products and eventually reduced the strength of concrete over time. However, the loss in the compressive strength of seawater concrete could be minimized by using a proper dosage of superplasticizer and retarder. The use of retarder kills the acceleration of cement hydration due to seawater and superplasticizer improves the fresh properties of seawater concrete, ultimately improving the concrete strength. Fig. 9 illustrates the improvement in compressive strength of seawater concrete due to the use of retarders and superplasticizers. The use of these chemical admixtures provides such seawater concrete that is comparable to conventional concrete (Younis et al., 2018).

2.6. *Durability*

It is essential to evaluate whether seawater used as mixing and curing water impacts the durability of concrete or not, which determines the service life of the concrete structure. There are various factors that affect the durability of seawater concrete compared to freshwater concrete, such as permeability, shrinkage, carbonation and sulfate attack. To assess the permeability of seawater concrete, Younis et al. (2018) conducted a study that concluded that the permeability of concrete was not affected when seawater was used for mixing. The concrete mixes prepared using freshwater and seawater exhibited nearly similar outcomes for water absorption, chloride migration, and chloride permeability tests. It was studied by Sikora et al. (2019) that the use of seawater in place of demineralized water refined the pore structure of cement paste and reduced the porosity by 12% at 28 days. In addition, Adiwijaya et al. (2017) and Montanari et al. (2019) also reported that concrete mixed with seawater had fewer pores and finer pore structure than concrete mixed with tap water. The decrease in the porosity of seawater mixed concrete may be due to the accelerated effect of seawater on the hydration of cement, which leads to a denser microstructure of concrete. It was also observed that the use of seawater resulted in the rapid production of C–S–H gel with higher surface area; therefore, the content of C–S–H gel in the concrete matrix caused by seawater is higher than that of C–S–H gel produced by tap water which led to decrease the porosity of concrete (Wang et al., 2018). Moreover, Etxeberria and Gonzalez-Corominas (2017) observed a decrement in the capillary absorption of concrete. The authors reported that it might be due to the filling of concrete pores by mineral salts present in seawater. Besides, Osman et al. (2021) investigated that bacterial concrete healed its cracks more efficiently when cured in seawater due to more production of calcium carbonate crystals than the control concrete and hence exhibited low permeability (Osman et al., 2021).

In addition, shrinkage is also an inherent characteristic of concrete, which affects its durability by inducing cracks in concrete and providing the entry of deleterious substances. It is not easy to save concrete from shrinking. Studies conducted by Mangi et al. (2020); Olutoge and Modupeola (2014) and Liu et al. (2022) showed a higher amount of drying shrinkage of concrete mixed with seawater as compared to concrete mixed with freshwater. Employing seawater for mixing in concrete resulted in a 6–9% higher drying shrinkage when compared to freshwater (Alomayri et al., 2023). Similarly, Younis et al. (2018) reported that the use of seawater displayed a small increment (within 5%) in the drying shrinkage of concrete. In the same way, in the study of Khatibmasjedi et al. (2019), a considerable increment was found in autogenous shrinkage, while a slight increment was reported in the drying shrinkage of concrete prepared with seawater than that of freshwater. Also, it was noted that reducing the ratio of water to cement reduced the impact of concrete shrinkage. Moreover, in the study of Park et al. (2010), the drying shrinkage of concrete increased considerably by increasing concrete chloride content. At the highest NaCl content of 1.2% by mass of cement, the drying shrinkage was found as 200 μs. In addition, the pure cement paste mixed with seawater showed a 48.5%

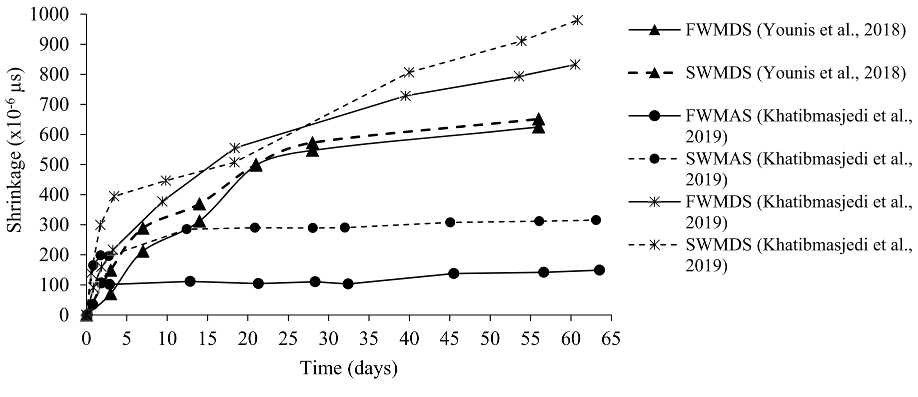

Fig. 10. Variation of drying shrinkage due to seawater mixing
(FWMDS- Freshwater Mix Drying Shrinkage, SWMDS- Seawater Mix Drying Shrinkage, FWMAS Freshwater Mix Autogenous Shrinkage, SWMAS- Seawater Mix Autogenous Shrinkage).

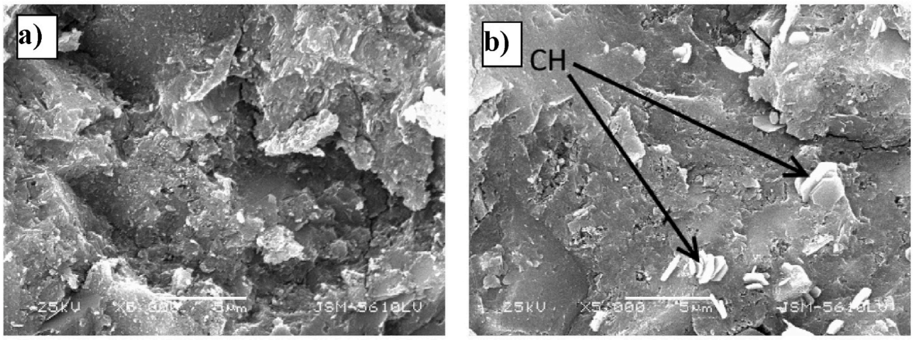

Fig. 11. SEM images of concrete containing 5% metakaolin along with (a) freshwater, (b) seawater at 28 days (Shi et al., 2015).

enhancement in autogenous shrinkage than the cement paste mixed with freshwater (Li et al., 2018). The reason behind the enhancement in autogenous shrinkage was found as the acceleration of the initial hydration of cement caused by seawater (Khatibmasjedi et al., 2019). Furthermore, it was observed that seawater refines the pore structure of concrete and leads to enhance the surface tension which results in increased drying shrinkage (Khatibmasjedi et al., 2019; Park et al., 2010; Younis et al., 2018). Thus, it could be said that the shrinkage of concrete increases by using seawater. So, in specific applications where shrinkage problems may occur, precautions should be exercised when preparing concrete with seawater. Though seawater is generally used in construction work which is going nearby the sea. This causes an increase in ambient humidity and may reduce the risk of concrete shrinkage. Besides, concrete shrinkage due to seawater could be regulated by restricting the water to cement ratio (Khatibmasjedi, 2018). The results found in previous studies regarding seawater's effect on concrete shrinkage are combinedly illustrated in Fig. 10 (Khatibmasjedi et al., 2019; Younis et al., 2018).

Furthermore, the carbonation of concrete was found to be reduced by using seawater. The deposition of seawater salts in concrete reduces the voids, and their water absorption property reduces the moisture content; hence there is a reduction in carbonation (Lollini et al., 2019). Nakajima et al. (1981) also reported that seawater led to a decrease in the carbonation rate of concrete than conventional concrete. Similarly, Pan et al. (2023) found that carbonation additionally improved the morphological characteristics of seawater, sea sand concrete, resulting in a denser and more compact matrix with reduced cracks and the formation of $CaCO_3$.

Moreover, sulfate erosion of concrete due to seawater is a significant concern in coastal and marine infrastructure, posing substantial challenges to the durability and longevity of concrete structures. Sodium sulfate (Na_2SO_4) and magnesium sulfate ($MgSO_4$) are typically present in seawater as sulfate compounds which react with specific components of OPC, including calcium hydroxide (CH), tricalcium aluminate (C3A), and mono-sulfoaluminate hydrate (C4ASH12). As a result Ettringite ($C_3A{\cdot}3CaSO_4{\cdot}32H_2O$), gypsum ($CaSO_4$) and brucite ($Mg(OH)_2$) are formed as shown in Eqs. (4)–(8). Their presence has consequences such as significant volume expansion (1.3–2.8 times) and subsequent cracking in concrete structures (Pratiwi et al., 2021). Magnesium sulfate (MgSO4) leads to more pronounced degradation compared to sodium sulfate. The formation of brucite leads to a pH reduction in the pore solution, diminishing the material's capacity to bind chloride ions and further compromising its durability. Also, $MgSO_4$ leads to a process called cation exchange, where calcium ions within the calcium-silicate-hydrate (C–S–H) gel are replaced by magnesium ions. This exchange results in the formation of magnesium-silicate-hydrate (M-S-H) as illustrated in Eq. (9). which also reduces the binding properties (Ting and Yi, 2023)

$$Na_2SO_4+Ca(OH)_2 + 2H_2O \rightarrow CaSO_4.H_2O + 2NaOH \tag{4}$$

$$C_3A + 3SO_4^{2-} + 3Ca(OH)_2 + 32H_2O \rightarrow C_3A{\cdot}3CaSO_4{\cdot}32H_2O\ \text{(Ettringite)} + 6OH^- \tag{5}$$

$$MgSO_4 + Ca(OH)_2 + 2H_2O \rightarrow CaSO_4.2H_2O + Mg(OH)_2 \tag{6}$$

$$3MgSO_4 + 3CaO.Al_2O.36H_2O + 6H_2O \rightarrow 3(CaSO_4.2H_2O) + 3\ Mg(OH)_2 + 2Al(OH)_3 \tag{7}$$

$$3MgSO_4 + C_3A.CaSO_4.12H_2O + 2H_2O \rightarrow 4(CaSO_4.2H_2O) + 3\ Mg(OH)_2 + Al_2O_3.3H_2O \tag{8}$$

$$C\text{–}S\text{–}H + Mg^{2+} \rightarrow M\text{-}S\text{-}H + Ca^{2+} \tag{9}$$

2.7. Role of SCMs to improve the performance of plain concrete with seawater

The utilization of Supplementary Cementitious Materials (SCMs) has been shown to mitigate the deleterious effects of sulfate erosion in concrete exposed to seawater. SCMs lead to reduction in the quantity of calcium hydroxide ($Ca(OH)_2$) through its consumption in pozzolanic reactions (Ting and Yi, 2023). Moreover, the reduction in the amount of $Ca(OH)_2$ due to its reaction with SCMs leads to enhance the solubility of hydrated C_3A. Thus, there are more chances of the sulfate and C_3A reacting through the solution phase instead of the solid phase, so the resulting expansion is less (Mather, 1964). Li et al. (2018) investigated that concrete mixed with slag and seawater performs better than concrete mixed with silica fume and seawater. The sulfates present in seawater enhance the slag reactivity by increasing its dissolution, so slag consumes more $Ca(OH)_2$ than silica fume.

SCMs also contribute to a more densely packed concrete structure by filling voids, thereby reducing vulnerability to sulfate attack (Ting and Yi, 2023). The interaction between SCMs and free $Ca(OH)_2$, formed in the early hydration stage of concrete, produces secondary C–S–H gel or tobermorite gel, which further plugs the pores of the concrete and reduces the permeability of concrete, thereby preventing the entry of seawater salts and enhances the durability of concrete. Particles of some SCMs are also finer than those of ordinary Portland cement, thus forming a denser concrete (Islam et al., 2010). In a study, metakaolin was found to refine the pore structure and enhance the resistance of concrete against seawater salts (Li et al., 2015). It was noticed that the use of metakaolin in concrete showed higher strength than ordinary concrete in both freshwater and seawater environments (Duan et al., 2012). Moreover, Shi et al. (2015) observed that the microstructure of concrete containing seawater and metakaolin was denser than the concrete prepared with freshwater and metakaolin, as shown in SEM images of Fig. 11.

Also, the combined use of silica fume (up to 15%) and fly ash (up to 40%) increased the strength and reduced the sorptivity and chloride permeability of seawater concrete (Ting et al., 2021). Moreover, the research of Etxeberria and Gonzalez-Corominas (2017) showed that the use of type III BFS cement with seawater in concrete minimized the

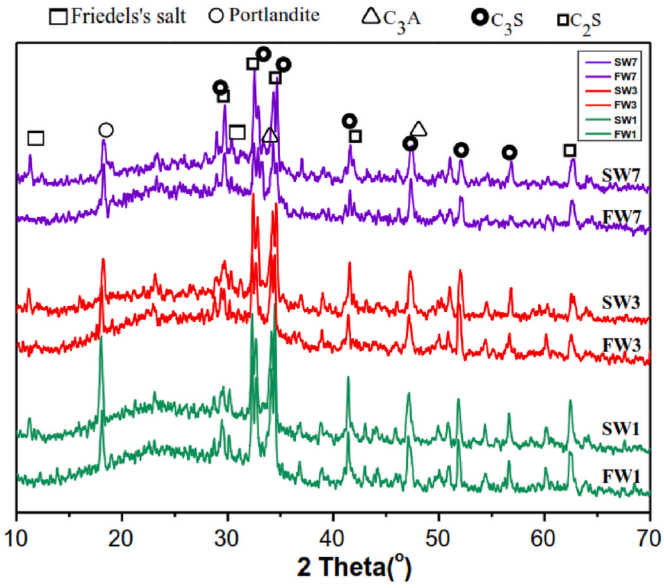

Fig. 12. XRD of Seawater (SW) and Freshwater (FW) concrete containing 0% slag (SW1, FW1), 25% slag (SW3, FW3) and 50% slag (SW7, FW7) (Li et al., 2018).

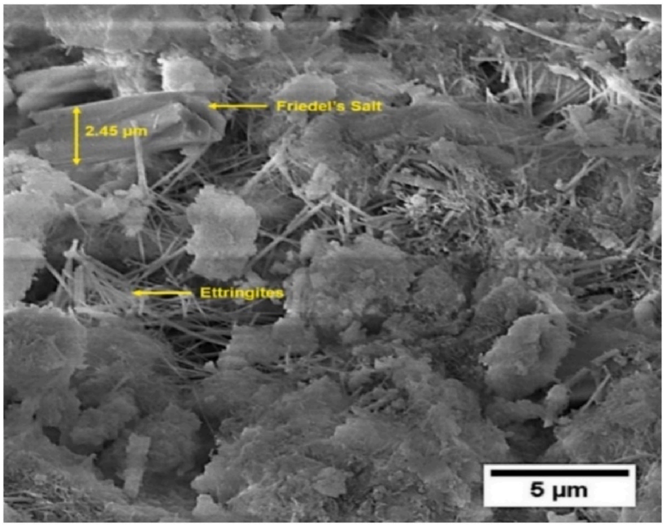

Fig. 13. SEM image of seawater concrete mix with SCMs depicting morphology of FS and Ettringite (Goyal and Karade, 2020).

pores and improved the electrical resistance of concrete than that of conventional concrete. In addition, the use of blast furnace slag (BFS) with seawater in also shows quite satisfactory results in steel reinforced concrete. The inclusion of BFS in concrete may decrease the oxygen around the steel reinforcement and minimize corrosion (Nishida et al., 2015). Further, it is also reported in a study that fly ash geopolymer structural concrete exhibits excellent resistance to chloride attack as opposed to ordinary concrete in the marine environment (Reddy et al., 2013). Kuang et al. (2023) examined that incorporating slag into the mixture reduced the need for activators and improves the pH of the pore solution, resulting in better strength retention. According to Nguyen et al. (2023), the utilization of sulfate-resisting cement is effective in mitigating the deleterious effects of seawater on concrete. Moreover, the 28 days compressive strength of concrete prepared with 30% cement replaced by calcined clay was found to be higher than conventional concrete (Zhou et al., 2017). Danner et al. (2018) reported 10% increment in compressive strength of mortar when 20% cement was replaced by calcined clay and also the pozzolanic reactivity was found to be greatest for clay particles less than 10 µm.

It was noticed that SCMs also bind the chloride anions present in concrete and form FS thereby reducing the chloride content in concrete. Alumina present in SCMs reacts with chloride anions to produce FS as shown Eq. (10) (Li et al., 2018; Qu et al., 2021).

$$3Ca(OH)_2 + CaCl_2 + Al_2O_3 + 7H_2O \rightarrow 3CaO.Al_2O_3.CaCl_2.10H_2O \qquad (10)$$

The X-ray Diffraction (XRD) test conducted by Li et al. (2018) on the concrete specimen prepared with seawater and slag confirmed the presence of FS, as shown in Fig. 12. The distinguished peaks of C_3S, C_2S, C_3A and $Ca(OH)_2$ were also observed. In addition, in the study of Goyal and Karade (2020), the morphology of FS in seawater concrete containing fly ash and red mud was observed as a hexagonal slice as depicted in Scanning Electron Microscopy (SEM) image of Fig. 13. However, the study of Montanari et al. (2019) reported that the amount of FS in seawater concrete decreased with the concrete age and it was found only 0.4% (by mass of cement paste) at 91 days. In a study conducted by Tadesse et al. (2023), the impact of seawater exposure on various cement samples, including Portland cement (PC), calcium aluminate cement (CAC), and calcium sulfoaluminate cement (CSA), was investigated. The findings revealed the formation of Friedel's salt due to the uptake of Cl^- by AFm phases. Specifically, monocarbonate, hemicarbonate, and C_2AH_8 were identified as the primary chloride binding phases in PC, CSA, and CAC, respectively.

3. Need of research and future prospects of plain concrete with seawater

Cement hydration with seawater has been extensively studied. There is a wealth of information available from various studies, and the basic principles and mechanisms are well understood by researchers in this field. Seawater can accelerate the process of early-age hydration in cement and reduce the setting time of concrete. This phenomenon also leads to improving the early strength of concrete, denser early microstructure and lesser permeability. Though, there is a reduction in the workability and the later strength of concrete. Moreover, the formation of Friedel's salt within the seawater concrete changes the way the crystals are arranged in the concrete, potentially affecting its properties. While this overall topic is well studied, there are specific areas where more research could be beneficial. In this case, there has been limited research focusing on the pore solution in seawater mixed concrete and understanding the composition and behavior of this pore solution. It also plays a crucial role in the hydration process and overall concrete performance. Further, the use of retarders, superplasticizers along with appropriate concrete mix design will possibly be helpful in minimizing the rapid hydration of cement and achieving required workability and strength. However, sufficient research on the effect of retarders on long-term seawater concrete properties is not available and is needed in this area.

In addition, there is a shortage of studies focusing on durability of seawater concrete under various environmental conditions such as freezing and thawing, wetting and drying, acid attack, etc. Detailed investigations into the fundamental mechanisms underlying the effects of seawater on concrete durability are essential. The past research indicates that seawater concrete is frequently used with SCMs, superplasticizers and retarders which serve to reduce the detrimental effects of seawater on concrete properties by lowering permeability, enhancing sulfate resistance, and immobilizing chloride ions. However, it remains unclear whether the presence of seawater directly augments the reactivity of SCMs in concrete. Future studies may explore this potential enhancement. Also, there is a lack of understanding regarding the specific and fundamental interactions between seawater concrete and chemical admixtures and future work should aim to elucidate these interactions. Moreover, the performance of admixtures to reduce

Table 5
The maximum allowed chloride content in concrete according to various codes.

Standard/ Code	Type or use of concrete	Max chloride (Cl^-) content	Comments
BIS-456 (2000)	Concrete without reinforcement	0.4	Acid soluble Cl^- (expressed as kg/m^3 of concrete)
	Reinforced concrete	0.6	
	Steam cure reinforced concrete and prestressed concrete	3.0	
BS-EN:206-1 (2000)	Concrete without reinforcement	1.0	Acid soluble Cl^- (expressed as % by mass of cement)
	Reinforced concrete with Sulfate Resisting Portland Cement (SRPC)	0.2	
	Reinforced concrete with cement other than SRPC	0.4	
	Prestressed concrete	0.1	
ACI-318 (2014)	Concrete with dry exposure	1.00	Water-soluble Cl^- (expressed as % by mass of cement for non-prestressed concrete)
	Concrete with moist exposer and no source of chlorides is present	0.30	
	Concrete with moist exposer and sources of chlorides are present	0.15	
	Prestressed concrete	0.06	
ACI-222R (2001)	Reinforced with dry exposure	0.20* 0.15**	* Acid soluble Cl^-** Water soluble Cl^-(% by mass of cement)
	Reinforced with wet exposure	0.10* 0.08**	
	Prestressed concrete	0.08* 0.06**	
NZS-3109 (1997)	Reinforced concrete with dry exposure	1.6	Acid soluble Cl^- (chloride expressed as kg/m^3 of concrete)
	Reinforced concrete exposed to moist or chloride environment	0.80	
	Prestressed concrete	0.50	

shrinkage in the context of seawater concrete is not well-understood. It's unclear whether they have the same effects as in freshwater concrete or if there are unique considerations when used with seawater concrete. Further research is needed to assess their effectiveness and compatibility.

4. Performance of reinforced concrete with seawater

4.1. Seawater concrete with common steel reinforcement

A number of reinforced concrete structures have been damaged or collapsed only because of the corrosion of steel reinforcement. The Mianus River Bridge in Greenwich, Connecticut, U.S. was collapsed on June 28, 1983 due to the corrosion of steel-reinforced bars and the formation of stalactites (*Mianus River Bridge, Wikipedia*). The Berlin Congress Hall in Germany collapsed on May 21, 1980 due to moisture ingress and corrosion of steel reinforcement (Borgard et al., 1989). Other recent incidents like the fall of the Gokhale bridge in Mumbai, India on July 3, 2018 (The-Hindu-Newspaper, 2018) and the total collapse of the Troja footbridge at Prague, the Czech Republic on December 2, 2017 (Schmalz, 1984) also happened due to the corrosion of steel reinforcement. The collapse of such structures resulted in the loss of lives and properties. It is worth mentioning that this corrosion process not only involves the chloride ions in seawater but also continues because of sufficient oxygen and moisture (Melchers and Li, 2006). Due to the presence of substantial amounts of chlorides in seawater, steel rebars come in contact with free chloride ions within a short duration, and the threat of corrosion of steel rebar increases (Igba et al., 2019; Kumar, 1998). When the chloride content in concrete exceeds the threshold limit, steel will change from a passive form to an active form; that is, the passivation layer on the steel will begin to deteriorate and resulting in corrosion of steel.

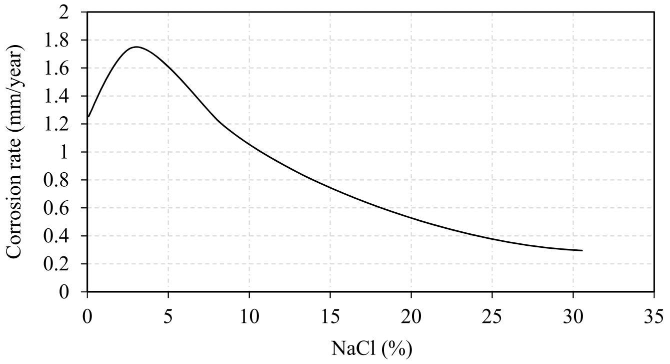

Fig. 14. Effect of sea salt on corrosion rate (Roberge, 2008).

There are different forms of chlorides present in concrete: 1) the chlorides which are chemically bound in concrete with different hydration products of cement are known as bound chlorides and 2) the chlorides which are present in free-state in pore fluid of concrete, known as water-soluble or free chlorides. The corrosion of steel bars is mainly due to the presence of these free chlorides. The total chloride present in concrete (free + bound) is known as acid-soluble chloride (Ahmad, 2003; Suryavanshi and Swamy, 1996). Different codes have provided the maximum limit of acid-soluble and water-soluble chlorides in concrete, as tabulated in Table 5.

Due to the high chloride content of seawater, a number of research have been performed on the degradation of steel in seawater concrete due to corrosion. The study by Dasar et al. (2020) concluded that seawater has a much higher effect on the corrosion of steel reinforcement when used for curing as compared to mixing. However, some other authors have noticed a substantial amount of corrosion in steel reinforcement when seawater is utilized to mix concrete (Chen et al., 2008; Makita et al., 1980). Roberge (2008) observed that the corrosion rate of steel reinforcement increased as the salt concentration in seawater increased but up to a value of 3.5%; after that, the corrosion rate decreased with increasing salt concentration, as seen in Fig. 14. Moreover, Melchers (2004) studied the pitting corrosion of steel in seawater and found that seawater would cause a lot of corrosion pits on the steel surface. The temperature of seawater played an important role in causing pitting corrosion. Conversely, the harmful effect of the chloride ions of seawater was observed to be reduced as the concrete age increased (Fukute et al., 1990; Otsuki et al., 2012). Physical properties of different steel bars are illustrated in Table 6. However, there is an urgent need for alternative reinforcement for making a successful reinforced concrete with seawater.

4.2. Seawater concrete with non-corrosive reinforcement

To address the challenge of steel rebar corrosion by using seawater, recent studies have employed anti-corrosion rebars. Reinforcing bars made of stainless steel have also been investigated for use in concrete structures as a substitute for carbon steel rebars. There are generally acceptable mechanical properties associated with stainless steel rebar. Generally, the ductility of hot-rolled stainless steel rebars is higher than that of carbon steel rebars, while cold-rolled rebars are less ductile (Medina et al., 2015). The EU-US Funded SEACON project explores how to use seawater safely to produce sustainable concrete reinforced with stainless-steel bars as non-corrosive reinforcement (Xiao et al., 2017). In particular, chromium embedded in the stainless steel gives anticorrosive features. However, chromium is expensive and scarce, as well as not

Table 6
Physical properties of different steel bars.

Types of bars	Modulus of elasticity (GPa)	Tensile strength (MPa)	Yield Strength (MPa)	Elongation (%)	Density (1000 kg/m^3)	Effect of seawater	Reference
Mild steel bars	186–210	340–680	250–370	15–21	7800–7870	Corroded when exposed to seawater	(Team Xometry, 2022)
High Strength Deformed Bars	–	≥485	415–550	8–14.5	–	Corroded when exposed to seawater	(Dailycivil.com)
Stainless Steel Bars (Grade 316)	190–205	480–620	205	40	7870–8070	high corrosion resistance	(AZO Materials, 2021)

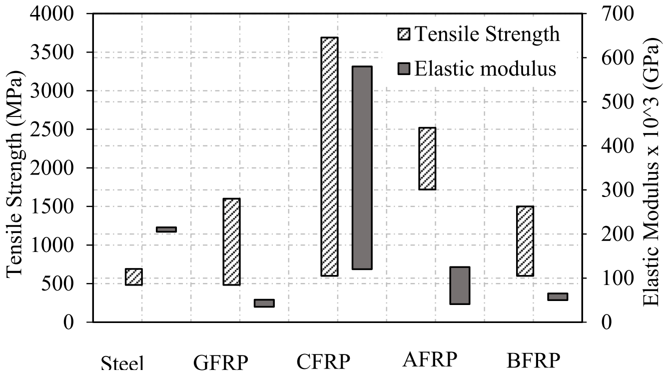

Fig. 15. Common ranges of tensile strength and elastic modulus of various reinforcement bars (ACI-440.1R, 2006; Ahmed et al., 2020).

readily available in sufficient quantity to make a significant replacement (Justnes, 2017). In comparison to carbon steel bars, stainless steel bars cost about 4–9 times more (Castro et al., 2003; García-Alonso et al., 2007). There is little knowledge about the behavior of structural members reinforced with stainless steel bars, which makes the use of stainless steel rebars in concrete structures still rare.

Fiber Reinforced Polymer (FRP) bars have also been considered as a replacement for traditional steel reinforcement (Jiang et al., 2012; Wu et al., 2007). The FRP bar is expected to become an alternative material to resolve the durability issue arising from steel reinforcement corrosion with seawater (Guo et al., 2020). It was found that there was a much lower effect on the efficiency of FRP bars due to high chlorides of seawater (Ceroni et al., 2006). The benefits of using FRP bars in concrete include higher resistance to corrosion and acid attack than steel bars; therefore, it is possible to use FRP bars safely with seawater. Moreover, FRP bars are lighter in weight and have a high strength-to-weight ratio (Bank, 2006). The weight of FRP bars is 1/4th to 1/5th of the weight of steel bars (ACI-440.1R, 2015). FRP composite comprises a system of fibers and polymer matrix. In the manufacturing of FRP bars, fibers are usually pulled and embedded with polymer resins by the pultrusion process. The polymer matrix holds the fibers firmly, makes an easy transfer of load among them, and prevents the bars from being affected by the harmful and aggressive environment (Ramôa Correia, 2013). FRP bars are generally categorized by the variety of fibers used. The most widely used FRP bars in the construction field are Glass Fiber Reinforced Polymer (GFRP) bars, Carbon Fiber Reinforced Polymer (CFRP) bars, Aramid Fiber Reinforced Polymer (AFRP) bars, and Basalt Fiber Reinforced Polymer (BFRP) bars (Qin et al., 2020). As per Ahmed et al. (2020) and ACI-440.1R (2006), CFRP bars have a high quality, and they have the highest tensile and elastic modulus as compared to other reinforcement bars. A comparison of tensile strength and elastic modulus of steel bars and different types of FRP bars is depicted in Fig. 15. However, CFRP bars are expensive due to the high cost of carbon fibers; hence they are not used much. Among these four types of FRP bars, GFRP bars are the most widely used due to the readily accessible sand is utilized in their manufacturing process, which also makes these bars economical (Nkurunziza et al., 2005). Furthermore, BFRP bars are also gaining attention for use as reinforcement in concrete with seawater. C. Lu et al. (2020) reported that the tensile strength of CFRP, BFRP, and GFRP bars reduced with time when immersed in tap water or seawater, as illustrated in Fig. 16. CFRP bars resisted the chemical attack better than the other 2 bars and BFRP bars were more deteriorated by seawater than GFRP and CFRP bars, whereas the BFRP and CFRP bars were slightly affected by tap water. The study by Wang et al. (2017) revealed that the durability of the GFRP bar was superior compared to the BFRP bar in the marine environment, particularly at elevated temperatures, because the property of the resin of GFRP bar was more resistant to the marine environment. In the study of Sharma et al. (2020), BFRP bars were used in seawater and sea sand concrete at different temperatures and found that BFRP bars tend to degrade at a high temperature (55 °C), but there is no major degradation of BFRP bars at low temperature (32 °C and 40 °C) in the marine environment. According to Guo et al. (2018), CFRP bars showed the best performance in the simulated marine environment, preceded by GFRP and BFRP bars. On the basis of several published research studies regarding the use of FRP bars, it can be outlined that FRP bars are beneficial as reinforcement in concrete with seawater due to the highly resistive corrosion property.

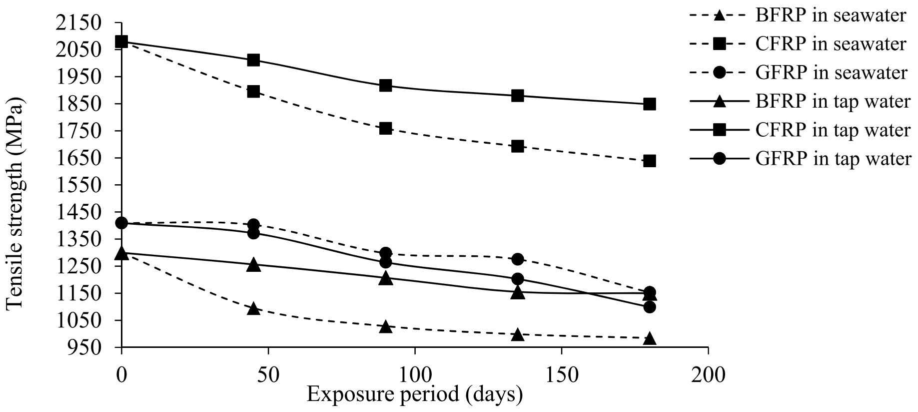

Fig. 16. Tensile strength of various FRPs immersed in tap water and seawater (C. Lu et al., 2020).

Although, there are also some disadvantages like FRP bars possess low ductility because they have an almost linear elastic stress-strain relationship up to rupture and then fail in a brittle way (Qin et al., 2020). Also, at higher temperatures, FRP bars start to soften, which leads to weakening the bond between concrete and FRPs, and there is the discharge of toxic volatiles and smoke by FRPs at high temperatures (Hu et al., 2018). When pure FRP comes in contact with nearly 300 °C temperature, there are great chances of combustion of FRP due to the thermal decomposition of the FRP matrix (Yu and Kodur, 2014). Moreover, FRP bars are non-weldable (Yuan and Zhu, 2012). According to ACI-440.1R (2006), there is also the possibility of the degradation of fibers of polymer bars by ultraviolet radiation. Besides, a humid environment would shorten the service life of glass fibers, while an alkaline environment is harmful to aramid and glass fibers. Urbanski et al. (2013) made a comparison study between the performance of beams reinforced with BFRP bars and conventional steel and found that the load carrying capacity of BFRP reinforced beams was much higher than the steel reinforced beams. BFRP reinforced beams showed 3 to 4 times greater deflection than steel reinforced beams because of lower elastic modulus of BFRP bars than steel bars. Also, cracks width in BFRP reinforced concrete was 4 times higher than the steel reinforced beams. Khanfour and Refai (2017) investigated the effect of low temperature (−20 °C) and freeze-thaw cycles on BFRP bars reinforced concrete. No significant effect was found on BFRP bars reinforced concrete when exposed to 100 and 200 freeze-thaw cycles, however, there was a 10% reduction in the bond strength of BFRP reinforced concrete specimens when exposed to low temperature. Lu et al. (2020) found great fall in the tensile and flexural strengths of concrete-covered and uncovered BFRP bars when immersed in ocean water and laboratory-accelerated marine environments. The fatigue bond mechanism of seawater sea-sand concrete (SSSC) reinforced with fiber-wrapped BFRP bars was studied by Xiong et al. (2022a,b) and it was found that BFRP fiber-wrapped bars developed fiber floccules due to wear and tear of white fiber wrapping under low-cycle loads. BFRP bars and SSSC ribs were effectively protected by these fiber floccules, further strengthening the mechanical interlock between them. Xiong et al. (2022a,b) reported that due to BFRP's low modulus, its strength was not entirely utilized, so the ultimate capacity of columns was mostly controlled by concrete's compressive strength. Wang et al. (2021) discovered that chloride ions and water molecules interact with the components of FRP bars, degrade the fiber-resin interface and causing the bars to lose their properties.

5. Need of research and future prospects of reinforced concrete with seawater

Previous studies have identified a gap in the research on FRP and stainless steel reinforced concrete, highlighting the need for further investigations into their performance under severe environmental conditions, including elevated temperatures, corrosive solutions, and sustained loading, as well as a lack of long-term data on the behavior of stainless steel and FRP in seawater mixed concrete. Therefore, further investigations are needed to evaluate their suitability and reliability for seawater applications. Moreover, past and ongoing studies have also suggested that aluminum bars could be another alternative reinforcement in concrete with seawater. Nowadays, aluminum is also used frequently after steel in civil engineering applications. Aluminum is popular due to its non-corrosive and non-combustible nature (Sapphire, 2017). Further, when aluminum or aluminum alloys are exposed to the atmosphere, they create a dense invisible oxide layer of Al_2O_3 on their surfaces. This layer protects the aluminum surface from corrosion by inhibiting further oxidation. In addition, aluminum's oxide layer makes it difficult to burn by obstructing the reaction between oxygen and metal (Alcan-Marine). Moreover, the aluminum bar shows a plastic behavior with a nominal yield state, which makes it suitable to use in earthquake-prone areas too (Skejić et al., 2016). In order to increase the stiffness and strength of aluminum, it is recommended to use aluminum alloy instead of pure aluminum for employing it as concrete reinforcement (Justnes, 2017). Aluminum is generally alloyed by using zinc, magnesium, silicon, manganese and copper (Xing and Ozbulut, 2016). Pure aluminum has a tensile strength of about 110 MPa, but when 5% magnesium is used for aluminum alloying, it shows about 274 MPa tensile strength, and for 10% magnesium, it can increase up to 395 MPa. In addition, concrete has a thermal expansion coefficient of 6–14 × 10^{-6} m/mK, whereas pure aluminum, GFRP and pure iron have 22 × 10^{-6}, 25 × 10^{-6} and 10 m/mK, respectively. Also, alloying aluminum with silicon can decrease its thermal expansion (Justnes, 2020). A comparison of the properties of steel, pure aluminum and aluminum alloy 6061 is tabulated in Table 7. Eide et al. (2018) used aluminum alloyed with 5% magnesium as reinforcement bars in concrete and found that the mechanical performance of steel and aluminum reinforced beams was comparable. Though, the bond strength of the concrete beam with aluminum bars was less than the concrete beam with steel bars and it was due to the smooth surface of aluminum bars which decreased the bond strength while the ribbed surface of steel bars increased the bond between steel and concrete. Therefore, it can be advocated to use ribbed surface aluminum bars to increase the bond strength. Due to all these properties, aluminum reinforcement could be a feasible alternative to other reinforcements in seawater concrete. However, there is a challenge in using aluminum as reinforcement in concrete because the outer layer of Al_2O_3 on the aluminum surface is degraded by the high pH of concrete (pH > 9), which leads to corrode the aluminum and generates hydrogen gas. The presence of calcium hydroxide in concrete increases the concrete's pH and reacts with aluminum, which substantially produces hydrogen gas as per Eq. (9) (Xing and Ozbulut, 2016).

Table 7
Properties of steel and aluminum (Eide et al., 2018; Xing and Ozbulut, 2016).

Properties	Steel	Pure aluminum	Aluminum alloy 6061
Young's Modulus, (GPa)	210	70	68.3
Ultimate tensile strength (MPa)	400	110	378.9

$$2Al + Ca(OH)_2 + 2H_2O \rightarrow Ca(AlO_2)_2 + 3H_2 \quad (9)$$

Xing and Ozbulut (2016) investigated that aluminum alloy bars could be used as reinforcement in concrete but after proper treatment. To use aluminum as a reinforcing material in concrete, inhibitors and insulating coatings could be utilized to prevent aluminum from being corroded. However, this treatment will add further costs to construction. So, there is a need to keep the pH of concrete so low that it will not degrade the aluminum. In this respect, the use of Supplementary Cementitious Materials (SCMs) in concrete is found to be beneficial because they consume calcium hydroxide produced by the hydration of cement and maintain the pH of concrete sufficiently low, thereby preventing corrosion of aluminum reinforcement bars (Justnes, 2020). A study published by Saha et al. (2018) indicated that fly ash reduced pore solution pH by binding alkali and lowering free calcium ions. Danner et al. (2015) used calcined marl to replace 50 % cement and did not find any traces of calcium hydroxide by XRD test after 2 years. Therefore, if used with a sufficient amount of SCMs in concrete, the aluminum reinforcement would further improve the durability of seawater concrete and there would be no corrosion due to chlorides of seawater.

Furthermore, there is growing interest in utilizing natural fibers as reinforcement in concrete. Various types of natural fibers including bagasse, sisal, jute, hemp, coconut, wool, hair, silk, asbestos etc. are readily found and derived from renewable sources (Hamada et al., 2023). The incorporation of natural fibers as a reinforcing material in concrete presents several advantages, including economic viability, lightweight characteristics, effective thermal and electrical insulation, high strength-to-weight ratio, biodegradability, and resistance to corrosion (Sanal and Verma, 2019). However, one drawback of

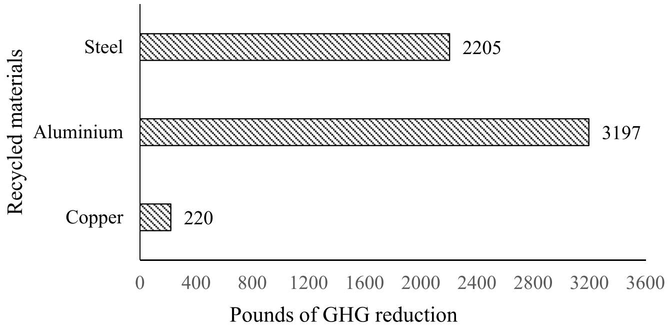

Fig. 17. Estimated GHG reductions per vehicle recycled (*Automotive Recycling Industry*, 2012).

employing natural fibers for concrete reinforcement lies in their vulnerability to the highly alkaline environment of concrete. The alkaline conditions lead to the degradation of lignin and hemicellulose present in the natural fibers. This degradation process disrupts the structure of cellulose nanocrystals and ultimately results in the deterioration of the natural fibers (Wei and Meyer, 2015). Addressing this challenge, researchers have explored the application of mineral additives to partially substitute cement content, thereby reducing the alkalinity of concrete and enhancing the durability of natural fibers. For instance, Filho et al., (2003) and Filho et al., (2009) successfully reduced alkalinity and improved the sisal fiber durability by partially replacing cement with calcined clay and slag. Similarly, Wei et al. reduced alkalinity and improved sisal fiber durability by replacing 30% of ordinary Portland cement with metakaolin (Wei and Meyer, 2015). Therefore, by leveraging the benefits of natural fibers combined with mineral additives, there is possibility to produce more durable and eco-friendly concrete utilizing seawater that meets the rising demand for sustainable building materials.

However, very limited research has been conducted on the long-term properties of seawater concrete with aluminum and natural reinforcement, necessitating further research to validate these findings. These reinforcements in concrete with seawater have been applied in very few field applications. It needs more research to have a better understanding of the tensile strength, modulus of elasticity and long-term bonding behavior of concrete with aluminum and natural reinforcement and how extreme conditions affect the service life of reinforced seawater concrete.

6. Towards a sustainable future in seawater reinforced concrete

The construction industry is facing challenges to attain sustainable progress without any adverse impact on the environment. The utilization of aluminum reinforcement in seawater concrete has the potential to mitigate the detrimental effects caused by seawater. However, it is important to consider that aluminum is a relatively expensive material, which can lead to an increase in construction costs. Conversely, incorporating recycled aluminum presents a promising opportunity to reduce the overall expenses associated with construction and brings sustainability. The rise in environmental awareness and social concerns attribute to the increasing demand for the recycling of aluminum (Wieman, 2018). In recent times, aluminum has been one of the most infinitely recyclable materials (Aluminum-Association, 2021). A virtual 100% recycling rate of aluminum is achieved without losing quality. It is also possible to reduce energy consumption by recycling aluminum. The manufacture of recycled aluminum only takes around 5% of the energy required to make new aluminum from bauxite (Rathi and Patil, 2013). The manufacturing of primary aluminum demands about 45 kWh per kilogram of metal produced, while recycling of aluminum needs only around 2.8 kWh per kilogram of metal produced (Kucharikova et al., 2017). Recycling each ton of aluminum conserves four tons of bauxite. Moreover, as an added benefit, hydroelectric power is used to produce aluminum in more than 50% of the world's industries, thus reducing the impact on the environment and promoting sustainability (Rathi and Patil, 2013). In addition, the automotive recycling industry recycles approximately 12.6 million vehicles annually. Typically, copper, aluminum and steel are recycled during this process. Recycling

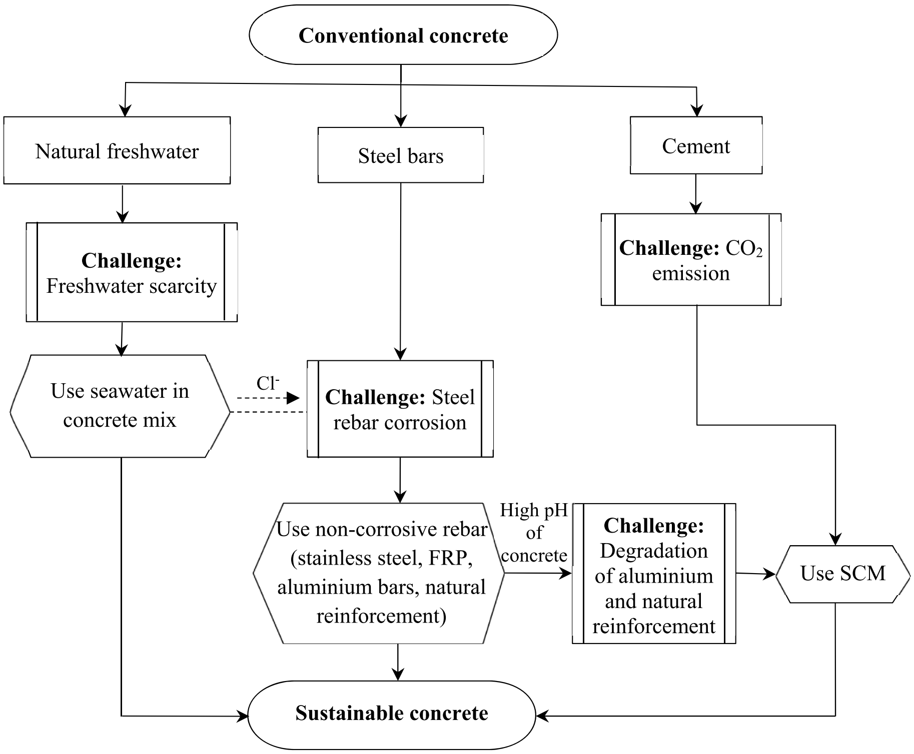

Fig. 18. The concept for achieving durable and sustainable concrete using seawater.

aluminum reduces about 3197 pounds of Greenhouse Gas (GHG) emissions per vehicle, much higher than recycling copper and steel, as shown in Fig. 17. Also, each year, recycling aluminum avoids the emission of over 90 million tons of carbon dioxide into the environment. As a consequence, recycled aluminum has a stronger case than it might seem at first glance when considering its use with seawater.

Additionally, the manufacturing of cement is considered the second biggest source of CO_2 emission (Justnes, 2020). The estimated global production of cement in 2022 was 4.1 billion tons (Garside, 2023). The cement manufacturing process is responsible for 5–8% of the total worldwide CO_2 emissions (GCCA, 2022; Javadabadi et al., 2019). The estimated CO_2 emission from cement production in 2021 was 1.7 billion metric tons (Garside, 2023). Europe is also facing significant environmental challenges due to CO_2 emissions from industries. To limit global warming and overcome environmental challenges, the European Union (EU) aims to achieve carbon neutrality by 2050. The role of the construction and civil sectors is of vital importance due to 20–30% global emissions of carbon dioxide (Huang et al., 2018). In this regard, the use of SCMs in concrete will help in reducing the emission of CO_2 into the environment. Over the past few decades, the search for different cement alternatives has been carried out. The use of industrial by-products such as fly ash, silica fume, bottom ash and BFS is beneficial for diminishing the harmful environmental impacts of concrete. However, there may be difficulties in accessing these materials and feeding the large cement industry continuously in the future. The production of these SCMs is connected with the CO_2 emission processes. It is expected that global fly ash production could reach 750 million tons a year (Ahmaruzzaman, 2010; Xin et al., 2022). In the upcoming time, coal will still be used to generate energy and fly ash production will no doubt be a problem (Panesar and Zhang, 2020). Therefore, their manufacturing may be limited in the upcoming time when blast furnace plants and coal power plants are substituted by fewer CO_2 discharge processes (Damtoft et al., 2008; Schneider et al., 2011). As a result, there is a need for the right pozzolanic material to replace cement for the long term.

Natural pozzolanic materials are available in abundant quantities worldwide. Some interesting works have also been performed on the use of natural pozzolanic materials to replace cement in concrete. Volcanic ash and calcined clay have been used successfully as natural pozzolanic materials in concrete (Hossain and Lachemi, 2007). An ample amount of volcanic ash is present in volcanic regions all over the world, and the use of such material for construction is becoming more prevalent. Judicious use of volcanic ash not only can turn it into a natural resource for low-cost construction materials, but also bring environmental sustainability. Moreover, the use of calcined clay leads to minimizing the discharge of CO_2 in the environment because the manufacturing of cement is considered as the second biggest source of CO_2 emission (Justnes, 2020). The calcination of 1 ton of cement at 1400–1450 °C temperature produces around 1 ton of CO_2 (*Cement kiln - Wikipedia*), whereas 0.3 tons of CO_2 is produced by 1 ton of calcined clay at 600–800 °C temperature, which is relatively lower as compared to cement production (Huang et al., 2017; Scrivener et al., 2018). The study of Baghban and Mahjoub (2020) also reported that calcined clay has the potential to reduce cement consumption adequately, which leads to a sustainable future. Though very few studies have been conducted using natural pozzolans in seawater concrete, it is necessary to investigate more about the long-term performance of seawater concrete containing natural pozzolans. Therefore, an approach to achieve a more durable and sustainable reinforced concrete with seawater is proposed as depicted in Fig. 18 and it is emphasized that the seawater concrete manufactured with non-corrosive reinforcement and natural pozzolans would alleviate the harmful impacts on concrete properties due to sea salts, increase its service life and enhance the sustainability in construction. The concrete thus obtained will be a step towards green and eco-friendly concrete construction practices, which is a need of an hour.

7. Conclusions

The discussion in this article noticeably shows that there is an urgent need for an alternative freshwater source for concreting as freshwater resources are continuously depleting. In this context, a large amount of available seawater is a reasonable alternative. Using seawater in construction work near the sea can conserve precious freshwater resources. A number of studies have found contradictory results regarding the effects of seawater in concrete as opposed to conventional concrete. In most studies, seawater produces equivalent or better results in plain concrete, despite some finding the opposite.

The aim of this study is to critically review the differences in plain and reinforced concrete performance induced by seawater, specifically in terms of fresh properties, mechanical properties, durability and sustainability and explore the differences that can influence the properties of seawater concrete. Notably, the primary concern in using seawater in concrete is the corrosion of steel reinforcement due to its high chloride content. On the contrary, FRP and stainless steel bars have been used as alternative reinforcement in concrete with seawater to reduce the severe threat of corrosion. However, there is a noticeable lack of long-term data on the behavior of stainless steel and FRP in seawater mixed concrete. Furthermore, some studies have explored the use of aluminum and natural reinforcement in seawater concrete, but both suffer from degradation caused by the high pH of concrete. To address this issue, the incorporation of sufficient quantities of pozzolans is suggested to adjust the pH of concrete, thus minimizing corrosion and damage to aluminum and natural reinforcement. Also, recycled aluminum, as an alternative to virgin aluminum for reinforcing concrete will not only reduce energy consumption but also lower the overall concrete costs and greatly enhance sustainability. Additionally, the substitution of natural pozzolanic materials for SCMs (typically obtained from industrial by-products) will help in reducing CO_2 emissions.

Therefore, in the case of coastal and marine infrastructure projects, seawater and non-corrosive reinforcement together with natural pozzolans are anticipated to significantly enhance the sustainability of reinforced concrete structures worldwide. However, it needs more attention to utilize seawater resources for concrete production. In brief, this review aims to summarize and compare seawater concrete with conventional concrete and offers insights into achieving more durable and sustainable seawater concrete based on emerging research.

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

No data was used for the research described in the article.

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