

Durability of cementitious materials in seawater environment: a review on chemical interactions, hardened-state properties and environmental factors

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1 **Durability of cementitious materials in seawater environment: A review on**
2 **chemical interactions, hardened-state properties and environmental factors**

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13 **Abstract**

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3 14 Global warming-induced sea level rise exacerbates the deterioration of maritime structures and
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5 15 imperils their long-term durability. Cementitious materials such as ordinary Portland cement
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7 16 (OPC), pozzolanic blended cement (PBC) and alkali-activated material (AAM) can chemically
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10 17 interact with seawater, leading to degradation of binding properties. Despite their extensive
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12 18 applications in construction industry, the seawater resistance of these materials remains elusive.
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15 19 The objective of this work is to review and compare the durability of OPC, PBC and AAM in
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17 20 seawater environment from the perspectives of chemical interactions and hardened-state
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20 21 properties. This paper first briefly explains the mechanism of seawater intrusion into hardened
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22 22 cementitious materials. The chemical interactions of chloride, sulphate and carbon dioxide
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24
25 23 from seawater with hydrate components in OPC, PBC and AAM are discussed. From the
26
27 24 durability aspects, this study evaluates and compares the performance of cementitious materials,
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30 25 including compressive strength, mass change, porosity and water absorption, and chloride
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32 26 permeability. Seawater deterioration mechanisms coupled with environmental factors such as
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35 27 wetting-drying cycle, external loading and temperature are also presented. Based on the review,
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37 28 future research is suggested to improve the durability studies related to seawater attack. This
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40 29 review provides better insight into the development of sustainable seawater-resistant
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42 30 construction materials for applications in seawater environment.

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45 31 **Keywords:** Cementitious binder, deterioration, durability, seawater, wetting-drying cycle
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33 1. Introduction

34 The rapidly growing construction industry over the last few decades has significantly increased
35 greenhouse gas emissions, contributing to global warming and hence sea level rise [1, 2].
36 According to recent studies, global sea level is projected to rise by 0.25 m to 0.3 m by 2050 [3]
37 and 0.6 m to 1.1 m by 2100 [4] if the emissions continue unabated. The sea level rise can
38 consequently increase the exposure of maritime structures to seawater attack, accelerating
39 material deterioration. Additionally, global warming can lead to extreme events such as coastal
40 flooding [5], intensified wave activity [6] and increased tidal range [7]. Existing structures that
41 have been designed using outdated guideline or without taking seawater attack into account
42 may no longer meet the durability requirements and may experience premature deterioration.
43 This will be a major concern for structures made of cementitious materials, which are
44 vulnerable to seawater-induced durability issues, such as corrosion, sulphate attack,
45 carbonation, hydrate leaching and strength deterioration [8]. Therefore, further research to
46 evaluate the seawater resistance of cementitious materials is essential.

47 Cementitious materials can be divided into several types based on their hydration mechanisms.
48 Ordinary Portland cement (OPC) is one of the most commonly used cementitious materials in
49 construction and building works. The hydration of OPC involves the conversion of tri-calcium
50 silicate (C_3S) into calcium silicate hydrate (C-S-H) and calcium hydroxide (CH) [9, 10]. C-S-
51 H is the main binder that contributes to strength, whereas CH is a secondary hydration product
52 that typically has low phase stability in aggressive environments. To improve binding
53 properties, pozzolans, such as fly ash (FA) [11], silica fume (SF) [12], ground granulated blast
54 furnace slag (GGBS) [13] and metakaolin (MK) [14], can be blended with OPC to form
55 pozzolanic blended cement (PBC). The pozzolans contain silica (SiO_2) and alumina (Al_2O_3) in
56 reactive crystalline form, which can react with CH to produce C-S-H and calcium aluminate
57 silicate hydrate (C-A-S-H). Meanwhile, the binding properties of these alumina/silicate-rich

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58 materials can also be activated by alkali solution, and this type of binder is known as alkali-
59 activated material (AAM). During AAM hydration, polymerization and silicate condensation
60 occur, which produces hydrates such as C-S-H, C-A-S-H and sodium aluminate silicate hydrate
61 (N-A-S-H) [15, 16]. Due to the varying contents of hydration products from OPC, PBC and
62 AAM, the deteriorating effects of seawater attack can differ. Thus, to better understand the
63 deterioration mechanisms, it is crucial to evaluate and compare the interactions of seawater
64 with OPC, PBC and AAM.

65 Seawater has properties that vary depending on geographical locations. The density of seawater
66 is about 1.025 g/cm³ at an ambient temperature of 25 °C [17]. Seawater is typically alkaline,
67 with pH values ranging from 7.4 to 8.2, and these properties are attributed to the presence of
68 salt [18]. Based on the published literature [19], the salinity of seawater in various marine
69 regions could range from 0.6% to 4.8%, with a generally accepted average salinity of 3.5%.
70 The chloride (Cl⁻) and sulphate (SO₄²⁻) contents of seawater account for 46.6%–77.5% and
71 4.9%–19.1% of total salt, respectively. In addition, increased carbon dioxide (CO₂) emissions
72 can be absorbed and dissolved in seawater to form carbonic acid, contributing to ocean
73 acidification [20]. The chemical interactions of these components in seawater with
74 cementitious materials could reduce hydrate stability and cause hydrate leaching,
75 compromising long-term material durability.

76 Previous research has studied and summarized the effect of seawater attack on cementitious
77 materials performance. Mangi et al. [21] briefly reviewed the engineering properties of
78 cementitious materials subjected to seawater attack, but the study was limited to assessing
79 strength and chloride penetration, which was insufficient to explain the deterioration
80 mechanism. A thorough study of the interactions of individual seawater components with
81 cementitious binder is essential to comprehend the seawater attack mechanism. Recent studies
82 [8, 19] have provided a more detailed review of the deterioration of OPC and PBC in marine

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83 environment, but these studies have reached different conclusions. Qu et al. [8] showed that
84 PBC was more durable than OPC, whereas Yi et al. [19] found that PBC was less stable in
85 seawater environment due to its lower alkalinity. As a result, further investigation is still needed
86 to iron out the discrepancy. Furthermore, the seawater resistance of AAM has not been reported
87 in these studies. Although OPC, PBC and AAM are widely used in the construction industry,
88 their seawater resistance has not been systematically documented and compared. Therefore,
89 the aim of this study is to provide a critical review on the durability of OPC, PBC and AAM in
90 seawater environment.

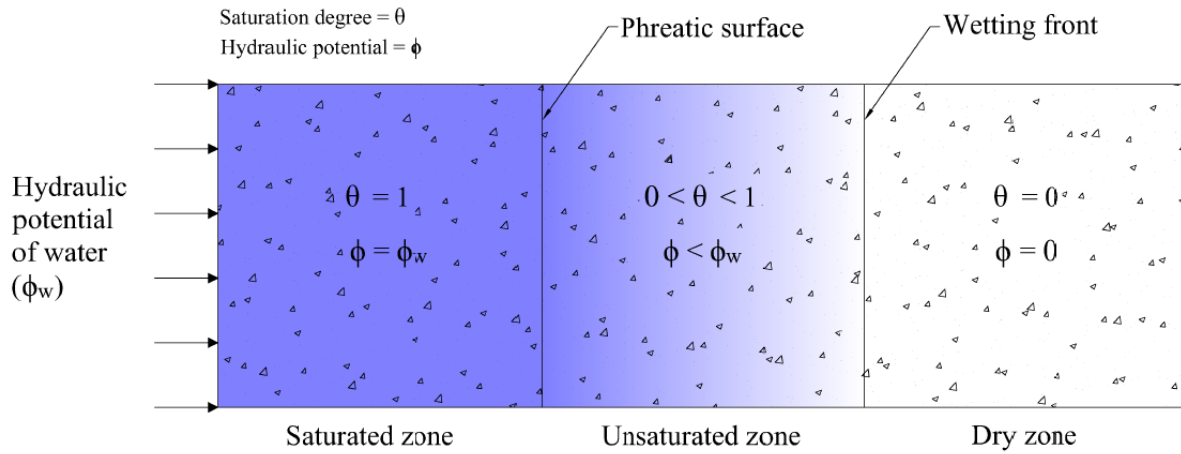
91 This review first delves into the mechanisms of seawater intrusion in hardened cementitious
92 materials. The chemical interactions of seawater with cementitious materials are then reviewed.
93 The impacts of seawater on the hardened-state properties are discussed. Lastly, the effects of
94 environmental factors such as wetting-drying cycle, external loading and temperature on
95 seawater attack are presented.

96 **2. Seawater transport mechanisms in hardened cementitious materials**

97 The cementitious materials can be exposed to seawater both internally (as mixing water) and
98 externally (in service). The influence of seawater used as mixing water is not included in this
99 study as it has been discussed elsewhere [18, 22, 23].

100 External seawater attack requires seawater infiltration into cementitious paste from the outside
101 via porous structure. The contact between external aqueous media and pore solution alters fluid
102 hydrostatic equilibrium, creating net mass flow. The seawater penetration and ionic transport
103 caused by aqueous solution motion is dominated by saturated and unsaturated flows [24].
104 Figure 1 shows the mass flow in cementitious matrix generated by surface water hydraulic
105 pressure (ϕ). The saturation degree (θ) maps out the zones of water flow, namely saturated zone

106 near the surface with pores totally filled with water, unsaturated zone with saturation degree of
 107 $0 < \theta < 1$, and dry zone with pores completely dry.



108
 109 **Figure 1. Water flow in porous cementitious matrix under hydraulic pressure [24, 25]**

110 In unsaturated condition, absorption and permeation are the main transport mechanisms in
 111 cementitious materials [25]. Absorption is defined as water uptake through capillary suction
 112 induced by partially saturated state of pore structure. Permeation is the transport of water into
 113 cementitious matrix in response to hydraulic pressure gradient. Due to the low porosity of
 114 cementitious materials, water movement is restricted to low volume flow and is regarded as
 115 laminar flow. The extended Darcy's law, as shown in Equation (1), can be used to describe the
 116 unsaturated flow in cementitious materials [26].

$$q = -\frac{\rho}{\eta} K \cdot \theta \cdot \phi \quad (1)$$

117 where q is flow rate, ρ is water density, η is water viscosity, K is unsaturated permeability, θ is
 118 degree of saturation and ϕ is hydraulic potential of water.

119 In saturated condition with no hydraulic potential gradient, the velocity of liquid is considered
 120 null. The ionic transport of seawater is mainly driven by electrochemical potential gradient.
 121 Diffusion, induced by chemical potential difference, transfers solutes from high concentration
 122 region to low concentration region [27]. Electrical coupling or electrical potential gradient is

123 also formed as a result of varying velocity of charged ions, in which faster ions accelerate
 124 slower ions via mutual attraction caused by opposite ionic charges [28].

125 There are other transport processes can affect the ionic movement in pore solution under
 126 saturated condition. The chemical reactivity of ionic species, such as ion-ion and ion-solvent
 127 interactions, has effect on the ionic flux, particularly in solution with high ionic strength [29].
 128 Thermal diffusion arising from gradient in non-isothermal condition facilitates ionic flux
 129 through the Soret effect [30]. The temperature difference also affects the ionic reactivity in
 130 pore solution by altering the solubility constant [31]. In brief, ionic transport in cementitious
 131 materials under saturated condition can be determined using the extended Nernst-Planck
 132 equation as shown in Equation (2) [28]. The R term in Equation (2) accounts for the change in
 133 local availability of ions in pore solution as a result of chemical interactions with cementitious
 134 materials, which is discussed in Section 3.

$$\frac{\partial(wc_i)}{\partial t} = \frac{\partial}{\partial x} \left(\underbrace{D_i w \frac{\partial c_i}{\partial x}}_{\text{diffusion}} + \underbrace{w c_i \frac{D_i z_i F}{r T} \frac{\partial \psi}{\partial x}}_{\text{electrical coupling}} + \underbrace{w D_i c_i \frac{\partial \ln \gamma_i}{\partial x}}_{\text{chemical reactivity}} + \right. \quad (2)$$

$$\left. \underbrace{\frac{w D_i c_i \ln(\gamma_i c_i)}{T} w \frac{\partial T}{\partial x}}_{\text{temperature}} \right) - R$$

135 where w is volumetric water content, c_i is concentration of ion i in solution, D_i is diffusion
 136 coefficient, z_i is valence number of ion i , F is Faraday constant, r is ideal gas constant, T is
 137 temperature of solution, ψ is electrical potential and γ_i is chemical activity coefficient.

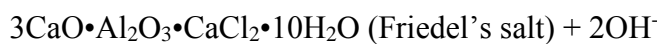
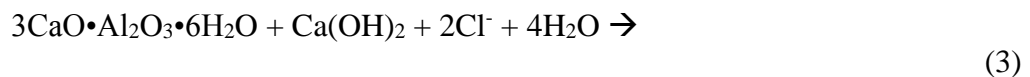
138 3. Chemical interactions of cementitious materials with seawater

139 To better understand the deterioration of cementitious materials, it is essential to examine their
 140 chemical interactions with seawater. This section discusses the chemical reactions of seawater
 141 with OPC, PBC and AAM.

142 3.1. Ordinary Portland cement (OPC)

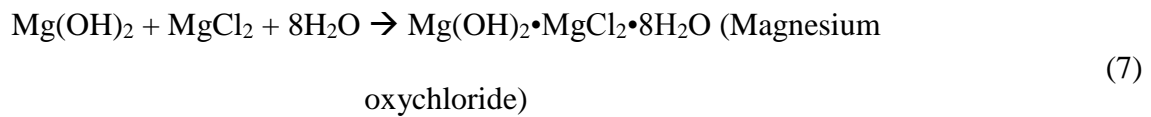
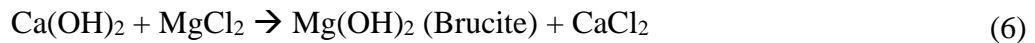
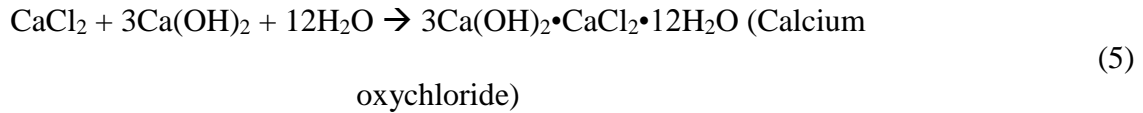
143 3.1.1. OPC with chloride

144 Chloride is one of the main components in seawater that can react with OPC. Aluminate ferrite
145 mono (AFm), tri-calcium aluminate (C₃A) and CH from OPC react with chloride to form
146 Friedel's salt (FS) (3CaO•Al₂O₃•CaCl₂•10H₂O) as shown in Equation (3) [8]. The formation
147 of FS involves two mechanisms, namely adsorption and anion-exchange [32]. FS is produced
148 in the former mechanism when chloride adsorbs on [Ca₂Al•(OH)⁻₆•2H₂O]⁺ of AFm. The latter
149 mechanism involves exchange of chloride with hydroxide (OH⁻) of AFm. Moreover, Kuzel's
150 salt (KS) (3CaO•Al₂O₃•0.5CaCl₂•0.5CaSO₄•10H₂O), a chloro-sulphoaluminate AFm phase, is
151 another product of reaction between chloride and AFm, as depicted in Equation (4) [33, 34].
152 KS has crystal structure that is made up of intercalation of FS and AFm [35]. FS can partially
153 convert to KS when exposed to low-chloride environment. The majority of studies [11, 36-38]
154 reveal that FS and KS have no negative impact on OPC. FS promotes hydration of aluminate
155 (C₃A) and ferrite (C₄AF), which could increase chloride binding capacity. The precipitation of
156 FS also densifies pore structure and reduces permeability.



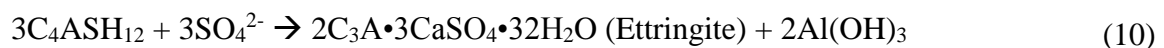
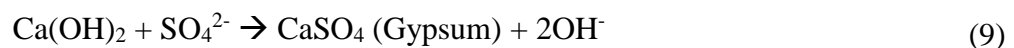
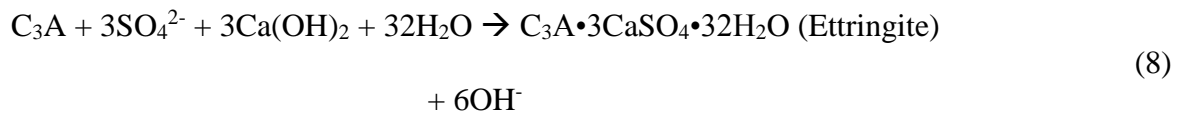
157 Another chloride reaction is the interaction of CH with calcium chloride (CaCl₂), which
158 produces calcium oxychloride (CAOXY) [3Ca(OH)₂•CaCl₂•12H₂O] as illustrated in Equation
159 (5) [39-41]. CAOXY exists in the atmosphere at temperature of 0–40°C and has three times the
160 volume of CH [42]. CAOXY crystals are prismatic and plate-shaped, and their precipitations
161 are expansive, which can cause destructive stress on pore. The leaching of calcium from CH
162 during CAOXY formation leads to hydrate dilution and hence binding strength loss. When

163 magnesium chloride (MgCl₂) is involved in the reaction, the damage is more severe due to the
 164 formation of brucite [Mg(OH)₂] and magnesium oxychloride [Mg(OH)₂•MgCl₂•8H₂O] as
 165 shown in Equations (6) and (7) [43]. The damage is exacerbated by the dissolution of C-S-H
 166 and formation of magnesium silicate hydrate (M-S-H) that has weaker cementitious property.



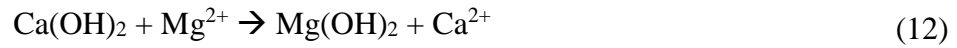
167 3.1.2. OPC with sulphate

168 Sulphate is another seawater component that can react with OPC. It is commonly found in
 169 seawater as sodium sulphate (Na₂SO₄) and magnesium sulphate (MgSO₄) [44]. The sulphate
 170 reacts with C₃A, CH and mono-sulphate hydrate (C₄ASH₁₂) to form ettringite
 171 (C₃A•3CaSO₄•32H₂O) and gypsum (CaSO₄), as shown in Equations (8)–(10) [45]. Ettringite
 172 and gypsum are formed within the pores of cementitious matrix and can cause 1.3 to 2.8 times
 173 volume expansion, resulting in cracking [46].



174 MgSO₄ causes more severe deterioration than Na₂SO₄ as cation-exchange of Ca in C-S-H and
 175 CH occurs to form M-S-H and brucite, which reduces the binding capability, as shown in
 176 Equations (11) and (12) [47]. Hydrates decalcification increases porosity and degrades

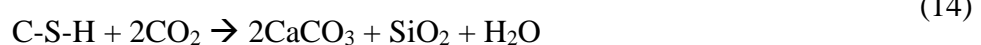
177 mechanical properties. The production of brucite lowers the pH of pore solution and reduces
178 the ability to bind chloride [48].



179 Besides, the coexistence of sulphate and chloride in seawater can influence the reactions with
180 OPC. When exposed to NaCl solution, Yoon et al. [49] found lower amounts of ettringite
181 formation during sulphate attack. The presence of chloride in seawater and its binding with
182 AFm phase to form FS slow down the precipitation of ettringite. The FS also lowers CH
183 concentration in pore solution, which converts ettringite into non-expansive and soluble low-
184 basic compound [50]. On the other hand, sulphate can also diminish the amounts of FS in
185 chloride reactions [51, 52]. Although the formation of FS is favored, FS can partially transform
186 into ettringite, especially under high sulphate concentration. The chloride binding capability
187 decreases because a fraction of AFm can interact with sulphate to form ettringite.

3.1.3. OPC with carbon dioxide

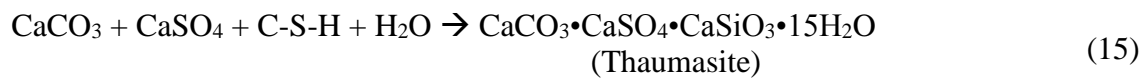
189 Carbon dioxide (CO_2) from the atmosphere can dissolve in seawater to react with CH and C-
190 S-H to form calcium carbonate (CaCO_3) as illustrated in Equations (13) and (14) [53]. The
191 reactions reduce the hydroxide concentration and lower the alkalinity in pore solution, affecting
192 hydrate stability and inducing hydrate dissolution [54]. The development of calcite and
193 depletion of C-S-H reduce the strength of OPC.



194 Carbonation can influence the chloride reactions in OPC. The carbonation lowers the pH of
195 pore solution and reduces the chloride binding capacity since FS and KS are decomposed into
196 free chloride [55]. The carbonation also decreases the CH available for FS formation.

197 According to Chang et al. [56], the free chloride content in OPC paste could be increased by
198 50% after 56-day carbonation. The chloride convection zone was also expanded by threefold
199 [57].

200 The presence of CaCO_3 induces another type of sulphate reactions with OPC. As shown in
201 Equation (15), a combination of sulphate and carbonate can react with C-S-H to form
202 thaumasite ($\text{CaCO}_3 \cdot \text{CaSO}_4 \cdot \text{CaSiO}_3 \cdot 15\text{H}_2\text{O}$), a non-cementitious compound [46]. The
203 transformation of C-S-H into thaumasite weakens the binding strength of OPC. Sibbick et al.
204 [58] showed that mortar sampled from the harbor walls after three years of sulphate attack was
205 porous and poorly degraded, with cement paste containing thaumasite in considerable amounts.
206 The reaction in Equation (15) is more favored at low temperatures ranging from 0 to 15°C,
207 because this temperature range facilitates the transition-state intermediate for thaumasite
208 precipitation [46, 59].



3.2. Pozzolanic blended cement (PBC)

3.2.1. PBC with chloride

211 Pozzolans are supplementary cementitious materials that can partially replace OPC to enhance
212 binding properties. Pozzolanic reaction in PBC refers to the chemical reaction of silica and
213 alumina with CH to form C-S-H and C-A-S-H. Since the main reactant CH, as shown in
214 Equations (3)–(6), is consumed in pozzolanic reaction, the reactivity of PBC with chloride
215 decreases. Past studies [39, 40] show that incorporation of reactive pozzolans like Class-F FA
216 and GGBS can impede the formation of CAOXY. The alumina in PBC is also capable of
217 binding chloride in the form of FS and KS [60]. The increased C-S-H content in PBC densifies
218 pore structure and reduces chloride permeability. Some studies [39, 61] show that the hydration
219 of alumina in PBC produces C-S-H with low calcium-to-silicon (Ca/Si) ratio and hence low

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6 220 chloride binding capability. However, it has little effect on the overall chloride binding capacity
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8 221 since the alumina hydration is secondary in PBC.

9 10 11 12 13 14 15 222 *3.2.2. PBC with sulphate*

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18 223 The sulphate attack resistance of PBC was generally higher than the OPC due to the following
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21 224 factors. First, the pozzolanic reaction produces more C-S-H that boosts the strength of PBC.
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23 225 Second, the CH content in PBC is low, leading to a less localized ettringite precipitation [44,
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26 226 59]. Third, the partial replacement of OPC with pozzolans lowers the overall C₃A content,
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28 227 which limits the development of ettringite and gypsum.

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31 228 Although PBC contains considerable amounts of alumina, its reaction with CH is advantageous
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33 229 in preventing sulphate attack. During pozzolanic reaction, CH binds with alumina to produce
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36 230 hydrotalcite [62, 63]. Since the alumina bound in hydrotalcite is inert, it will not contribute to
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38 231 the production of ettringite. However, pozzolans with low reactivity can result in more alumina
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40 232 available for ettringite formation. Ogawa et al. [64] revealed that, while the hydration of GGBS
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42 233 reduced the sulphate ingress, unreacted alumina might still transform into ettringite. Hence, an
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44 234 optimum replacement ratio and proper curing methods are essential to achieve the benefits of
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46 235 PBC in terms sulphate resistance.

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49 236 Some studies [44, 48] show that PBC is more susceptible to MgSO₄ attack than OPC. Aye and
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51 237 Oguchi [48] found that the strength loss of SF mortar and FA mortar in MgSO₄ attack was 9%
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53 238 and 2% more than that of OPC mortar. Nehdi and Hayek [44] reported that PBC mortar exposed
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55 239 to MgSO₄ solution was significantly damaged with surface scaling and mass loss, whereas the
56
57 240 OPC mortar exhibited less surface deterioration. The pozzolanic reaction of PBC consumes
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59 241 CH and reduces the pH buffer in pore solution, resulting in cation exchange between MgSO₄
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61 242 and C-S-H. The MgSO₄ attack causes decalcification, in which the Mg²⁺ cations react with C-
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63 243 S-H and form cohesionless M-S-H.
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244 3.2.3. *PBC with carbon dioxide*

245 The CO₂ reactions deteriorate PBC more severely than OPC. As CH is consumed during
246 pozzolanic reaction, the cementitious matrix loses pH buffer, resulting in direct carbonation of
247 C-S-H. Besides, because the carbonation process occurs from the outer to the inner layer, the
248 formation of CaCO₃ can generally act as a barrier to prevent further CO₂ penetration. However,
249 since the concentration of CaCO₃ in PBC is low due to the reduced CH, the barrier becomes
250 thinner, making the C-S-H more susceptible to carbonation. Moreover, the C-S-H formed in
251 PBC has low Ca/Si ratio, which accelerates the carbonation process [65]. Other hydrates such
252 as C-A-S-H and aluminate phase are amorphous and disordered, and can be easily degraded
253 during carbonation [66].

254 3.3. *Alkali-activated materials (AAM)*

255 3.3.1. *AAM with chloride*

256 AAM binds chloride through surface adsorption on C-A-S-H and N-A-S-H gels [67]. The
257 electrostatic charge between gels and chloride creates Van der Waals force for physical
258 adsorption. Besides, the pore solution of AAM is alkaline, which exhibits high ionic strength
259 and facilitates surface adsorption [68]. The hydrotalcite in AAM also contributes to chloride
260 binding. The chloride pairing with sodium ions can be adsorbed on the diffuse layer of
261 hydrotalcite [69]. Chloride is also bound by hydrotalcite when aluminate phases (C₃A) react
262 with chloride via anion-exchange [70]. In addition, statlingite, is another AFm hydrate found
263 in AAM that can bind chloride [71]. Chloride can be bound by statlingite through surface
264 adsorption and lattice substitution.

265 3.3.2. *AAM with sulphate*

266 N-A-S-H and hydrotalcite in AAM are less reactive with sulphate and have high resistance to
267 de-alumination [72-74]. However, sulphate can be physically adsorbed and bound on C-A-S-
268 H through electrostatic force. This may promote the reactions between C-A-S-H and sulphate

269 to form ettringite and gypsum. Sulphate reactions with unreacted magnesia and aluminate in
270 slag-based AAM can also form these deterioration products. Several published literatures [72,
271 73, 75] indicate that AAM is vulnerable to MgSO_4 -induced sulphate attack. The Mg ions from
272 MgSO_4 can replace the Ca ions in C-A-S-H and Na ions in N-A-S-H to form magnesium
273 alumina-silicate hydrate (M-A-S-H). Expansive products of brucite and gypsum are also
274 formed. Since AAM lacks buffering due to the absence of CH, its pH can drop rapidly during
275 MgSO_4 attack, which results in decalcification of C-A-S-H [72, 75]. This decreases the molar
276 ratio of Ca/Si, leading to further release of Ca ions from C-A-S-H. Nonetheless, the molar ratio
277 of Al/Si in AAM will remain constant because de-alumination is less likely to occur.

278 3.3.3. AAM with carbon dioxide

279 When CO_2 interacts with C-A-S-H and N-A-S-H in AAM, carbonate compounds such as
280 calcite, aragonite, vaterite, natron ($\text{Na}_2\text{CO}_3 \cdot 10\text{H}_2\text{O}$) and trona ($\text{Na}_2\text{CO}_3 \cdot \text{NaHCO}_3 \cdot 2\text{H}_2\text{O}$) are
281 formed [76-78]. The carbonated C-A-S-H typically has a low Ca/Si ratio but contains a highly
282 cross-linked alumina-silicate phase. The alumina-silicate phase is generally stable due to its
283 highly polymerized structure. N-A-S-H, on the other hand, is more porous than C-A-S-H and
284 thus more easily carbonated. The formation of natron and trona, also known as sodium
285 carbonate and sodium bicarbonate, is responsible for the carbonation of N-A-S-H. N-A-S-H
286 carbonation can occur in two stages: (i) carbonation of sodium hydrate to form sodium
287 carbonate and (ii) establishment of phase equilibrium between carbonate and bicarbonate [79].
288 According to Zhang et al. [80], a high-alkalinity environment encourages carbonate formation,
289 whereas a low-alkalinity environment favors bicarbonate formation. Nevertheless, the
290 hydrotalcite phase in AAM is capable of decreasing the carbonation by acting as CO_2 sorbent
291 [81].

292 3.4. Summary

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2 293 OPC, PBC and AAM are susceptible to seawater attack due to interactions with chloride,
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4 294 sulphate and CO₂. Table 1 provides a summary of these chemical reactions. Chloride reactions
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7 295 cause minimal damage to the cementitious materials, as chloride can be effectively bound by
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10 296 hydration products such as FS, KS and hydrotalcite. On the other hand, sulphate reactions cause
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12 297 more severe damage due to the formation of deterioration products like ettringite, gypsum and
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14 298 brucite. The carbonation also depletes C-S-H and CH, reducing the binding properties of
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17 299 cementitious materials. Although the effects of chloride, sulphate and CO₂ have been evaluated
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19 300 individually, the literature review indicates that there exists a synergy among these components
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22 301 in the actual seawater environment. Thaumasite, for example, is formed through a combination
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24 302 of sulphate and carbonate reactions. The coexistence of chloride and sulphate also influences
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27 303 reactions of each other, affecting formation of FS and ettringite. However, there is still a lack
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29 304 of understanding on the mutual interactions of these seawater components. Furthermore,
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32 305 seawater compositions are not constant and vary in salinity, making it difficult to accurately
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34 306 assess seawater attack mechanisms. In this context, future study should look into the combined
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36 307 interactions of chloride, sulphate and CO₂ with cementitious materials in seawater by
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39 308 considering a wide range of composition ratios.

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Table 1. Summary of seawater reactions with OPC, PBC and AAM

Cementitious materials	Reactants		Product	Findings	Ref
	In seawater	In binder			
OPC	<u>1. Chloride</u>				
	• Chloride ion (Cl ⁻)	• Tri-calcium aluminate (3CaO•Al ₂ O ₃ •6H ₂ O)	• Friedel’s salt (3CaO•Al ₂ O ₃ •CaCl ₂ •10H ₂ O)	• Forming through anion-exchange and adsorption on AFm • Immobilize chloride and densify pore structure, reducing permeability	[8, 32]
		• Calcium hydroxide (Ca(OH) ₂)			
	• Chloride ion (Cl ⁻)	• Tri-calcium aluminate (3CaO•Al ₂ O ₃ •6H ₂ O)	• Kuzel’s salt (3CaO•Al ₂ O ₃ •0.5CaCl ₂ •0.5CaSO ₄ •10H ₂ O)	• Similar properties to Friedel’s salt, but exhibit lower chloride binding capability	[33, 34]
		• Calcium hydroxide (Ca(OH) ₂)			
		• Calcium sulphate (CaSO ₄)			
	• Calcium chloride (CaCl ₂)	• Calcium hydroxide (Ca(OH) ₂)	• Calcium oxychloride (3Ca(OH) ₂ •CaCl ₂ •12H ₂ O)	• Prismatic and plate-shaped crystals that are expansive	[39-41]
	• Magnesium chloride (MgCl ₂)	• Calcium hydroxide (Ca(OH) ₂)	• Magnesium oxychloride (Mg(OH) ₂ •MgCl ₂ •8H ₂ O)	• Reactions cause loss of hydrate	[43]
		• Calcium silicate hydrate (C-S-H)	• Magnesium silicate hydrate (M-S-H) • Brucite (Mg(OH) ₂)	• More severe deterioration than CAOXY formation • Dissolution of C-S-H and hence strength loss	
		<u>2. Sulphate</u>			
	• Sulphate ion (SO ₄ ²⁻)	• Tri-calcium aluminate (C ₃ A)	• Ettringite (C ₃ A•3CaSO ₄ •32H ₂ O)	• Form within pore to cause expansion and damage • Deplete hydrate, resulting in porous structure	[45]
		• Calcium hydroxide (Ca(OH) ₂)	• Gypsum (CaSO ₄)		
• Magnesium sulphate (MgSO ₄)	• Calcium silicate hydrate (C-S-H)	• Magnesium silicate hydrate (M-S-H) • Brucite (Mg(OH) ₄)	• Cation exchange with C-S-H gel to form weaker M-S-H gel • Reduce pH and chloride binding	[47, 48]	
	• Calcium hydroxide (Ca(OH) ₂)				
	<u>3. Carbon dioxide</u>				
• Carbon dioxide (CO ₂)	• Calcium silicate hydrate (C-S-H)	• Calcium carbonate (CaCO ₃)	• Reduce pH and corrosion resistance • Decompose FS into free chloride • Dissolution C-S-H and reduce strength	[53, 54]	
	• Calcium hydroxide (Ca(OH) ₂)				

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	<ul style="list-style-type: none"> • Calcium carbonate (CaCO₃) • Calcium sulphate (CaSO₄) 	<ul style="list-style-type: none"> • Calcium silicate hydrate (C-S-H) 	<ul style="list-style-type: none"> • Thaumasite (CaCO₃•CaSO₄•CaSiO₃•15H₂O) 	<ul style="list-style-type: none"> • Non-cementitious compound formed at temperature of 0–15 °C • Reduce strength and cause cracking of cementitious materials 	[46, 58, 59]
PBC	<p><u>1. Chloride</u></p> <ul style="list-style-type: none"> • Chloride ion (Cl⁻) <p><u>2. Sulphate</u></p> <ul style="list-style-type: none"> • Magnesium sulphate (MgSO₄) <p><u>3. Carbon dioxide</u></p> <ul style="list-style-type: none"> • Carbon dioxide (CO₂) 	<ul style="list-style-type: none"> • Alumina (Al₂O₃) <ul style="list-style-type: none"> • Calcium silicate hydrate (C-S-H) <ul style="list-style-type: none"> • Calcium silicate hydrate (C-S-H) • Calcium aluminate silicate hydrate (C-A-S-H) • Aluminate phase 	<ul style="list-style-type: none"> • Friedel's salt (3CaO•Al₂O₃•CaCl₂•10H₂O) • Magnesium silicate hydrate (M-S-H) • Calcium carbonate (CaCO₃) 	<ul style="list-style-type: none"> • Immobilize free chloride • Bind less chloride due to low C-S-H with low Ca/Si ratio • More severe damage than in OPC due to low CH content, resulting in direct reactions with C-S-H • Low CH content accelerates carbonation of C-S-H • C-S-H with low Ca/Si ratio is more vulnerable to carbonation 	[60, 61] [44, 48] [55, 65, 66]
AAM	<p><u>1. Chloride</u></p> <ul style="list-style-type: none"> • Chloride ion (Cl⁻) <p><u>2. Sulphate</u></p> <ul style="list-style-type: none"> • Magnesium sulphate (MgSO₄) <p><u>3. Carbon dioxide</u></p> <ul style="list-style-type: none"> • Carbon dioxide (CO₂) 	<ul style="list-style-type: none"> • Aluminate phase (C₃A) <ul style="list-style-type: none"> • Calcium aluminate silicate hydrate (C-A-S-H) • Sodium aluminate silicate hydrate (N-A-S-H) <ul style="list-style-type: none"> • Calcium aluminate silicate hydrate (C-A-S-H) • Sodium aluminate silicate hydrate (N-A-S-H) 	<ul style="list-style-type: none"> • Hydrotalcite • Statlingite • Magnesium aluminate silicate hydrate (M-A-S-H) • Brucite (Mg(OH)₂) • Gypsum (CaSO₄) • Calcite (CaCO₃) • Aragonite (CaCO₃) • Vaterite (CaCO₃) • Natron (Na₂CO₃•10H₂O) • Trona (Na₂CO₃•NaHCO₃•2H₂O) 	<ul style="list-style-type: none"> • Bind chloride through adsorption on hydrates surface • High resistance to de-alumination during sulphate attack • Lack of CH increases vulnerability to cation exchange caused by MgSO₄ • Carbonated C-A-S-H remains stable due to highly polymerized structure • N-A-S-H is more easily carbonated due to porous structure, forming carbonate and bicarbonate compounds 	[67, 69, 71] [72, 73, 75] [76-78]

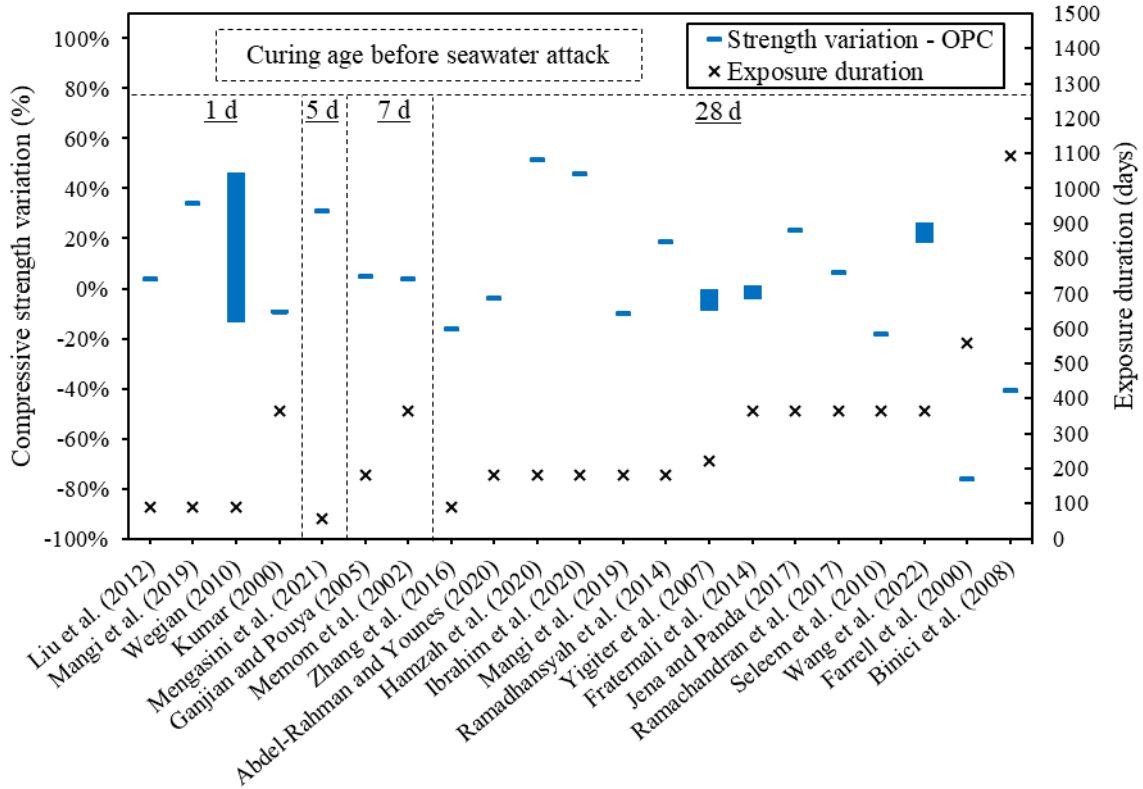
4. Hardened-state properties of cementitious materials exposed to seawater attack

The interactions of cementitious materials with seawater modify the hydrate phases and gel structures, as well as generates deterioration products, all of which have direct and considerable impacts on the durability properties. To elucidate the implications on durability, the hardened-state properties of cementitious materials after external seawater attack are discussed in this section.

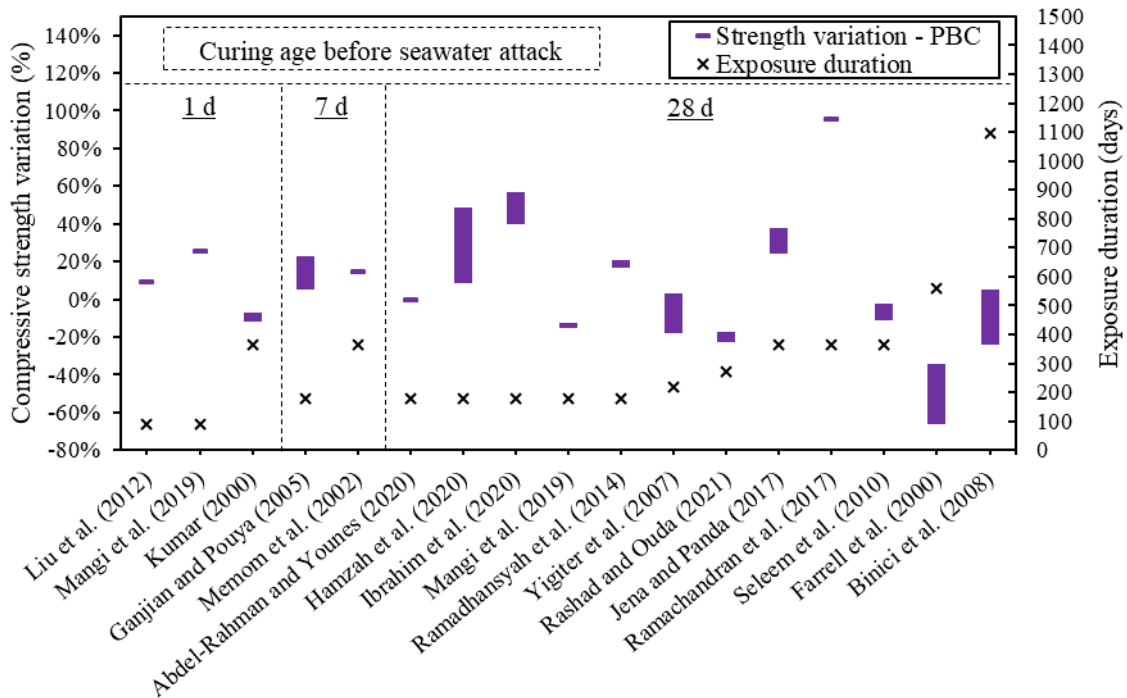
4.1. Compressive strength variation

Compressive strength has been used in numerous investigations to measure the resistance of cementitious materials against seawater attack. In this study, the compressive strength variation caused by seawater attack is determined using data gathered from the literature. This analysis incorporates the experimental results for cementitious materials used in paste, mortar and concrete. Although the literature contains a variety of mixture proportions, the same cementitious mixture types have been used in the individual calculation for comparison.

Figure 2 to Figure 4 depict the compressive strength variation for OPC, PBC and AAM. The literature reveals inconsistent effects of seawater on the compressive strength, with some studies [14, 82-96] showing a decrease in strength and others [97-107] showing an increase in strength. The results disparity is attributed to two factors: curing age and exposure period. The literature in Figure 2 to Figure 4 has been grouped based on curing age of cementitious materials before seawater attack. Specimens with shorter curing times, such as 1, 5 and 7 days, generally experience strength gain due to the ongoing hydration. In this case, the hydration effect overwhelms the deterioration caused by seawater reactions. The seawater exposure period for each study is also shown in Figure 2 to Figure 4. The seawater attack is long-term process that causes more evident strength deterioration only after prolonged exposure periods (i.e. more than 365 days).

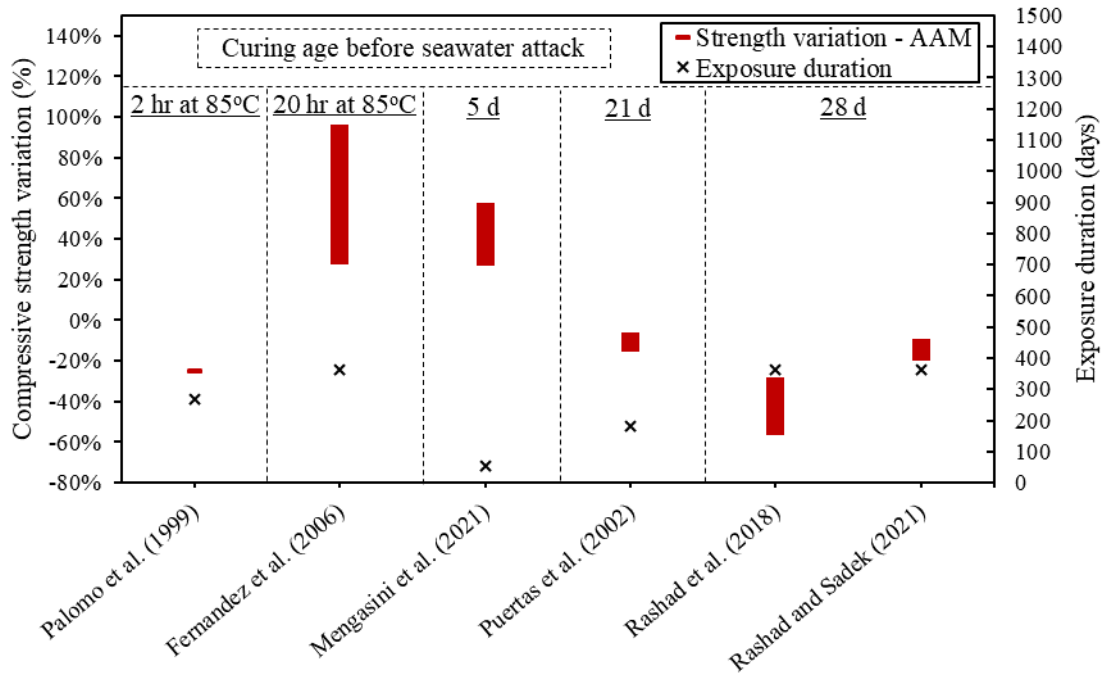


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337 **Figure 2. Compressive strength variation of OPC under seawater attack (data adapted**
338 **from [82, 88-107])**



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340 **Figure 3. Compressive strength variation of PBC under seawater attack (data adapted**
 341 **from [14, 82, 90-93, 95-97, 99-105, 107])**



342
 343 **Figure 4. Compressive strength variation of AAM under seawater attack (data adapted**
 344 **from [83-87, 98])**

345 There are several factors that contribute to the strength deterioration of cementitious materials.
 346 First, the chloride, sulphate and CO₂ from seawater gradually reacts with cementitious paste
 347 and decalcifies the C-S-H. Salt crystals also form on the surface of cement paste, causing
 348 crystallization pressure [95]. The seawater resistance of cementitious materials depends on the
 349 binder content. For example, increase in OPC content from 250 kg/m³ to 350 kg/m³ could reduce
 350 strength loss from 9% to nearly 0% [82]. Higher binder content increases paste volume and
 351 promotes better bonding. But, further increase in OPC content has detrimental effect due to
 352 higher C₃A content, which triggers sulphate attack [90]. Long-term seawater exposure causes
 353 significant strength loss. But, the strength loss will occur faster if seawater is high in salinity

1 354 and contains a huge quantity of sulphate salts, particularly $MgSO_4$, which can cause expansive
2 355 damage and hydrate dissolution.
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5 356 Some studies, however, show that seawater attack improves strength. The salt precipitated from
6
7 357 seawater within the cementitious matrix can reduce porosity and enhance strength temporarily
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10 358 [103]. The cementitious matrix is also enhanced by filling of pores with Friedel's salt from
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12 359 chloride reactions. The formation of ettringite from sulphate reactions also densifies the pore
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14 360 structure. The cementitious matrix continues to hydrate during seawater attack, with the curing
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16 361 effect outweighs the seawater-induced damage. But, the curing effect diminishes as the
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18 362 exposure duration increases. Ibrahim et al. [105] showed that the strength gain of concrete
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20 363 peaked at 60 days, and decreased by 7%–13% at 180 days. Jaya et al. [97] reported that the
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22 364 peak strength gain occurred between 30 and 60 days. The delayed strength deterioration could
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24 365 be ascribed to the low salinity of seawater [106]. During this period, strength is gained due to
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26 366 pore densification, but it then declines due to over-accumulation of expansive products and
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28 367 loss of hydrate.
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35 368 PBC and AAM are generally more resistant to seawater attack than OPC as shown in Figure 3
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37 369 and Figure 4. OPC has the greatest compressive strength loss, with variation ranging from -76%
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39 370 to 51.4%. The use of PBC and AAM slightly reduces the strength loss, with variation of -50%
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41 371 to 95.2% and -42.1% to 62% respectively. The hydration of pozzolanic materials considerably
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43 372 enhances the strength, producing more hydrate gels to withstand expansive damage and resist
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45 373 hydrate dissolution. The conversion of CH into C-S-H compacts the pore structure and hence
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47 374 minimizes seawater intrusion. The use of ternary blended cements further lowers the strength
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49 375 degradation [103]. As for AAM, it has higher early strength than OPC, making it more resistant
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51 376 to seawater attack [98]. The use of thermal curing accelerates the hydration of AAM [86, 87].
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53 377 Seawater promotes geo-polymerization of unreacted aluminate and silicate, which improves
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5 378 strength and suppresses degradation [84]. AAM also contains fewer high-calcium phases and
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7 379 is less susceptible to seawater-induced decalcification.

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10 380 In summary, the effect of seawater on compressive strength varies depending on curing
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12 381 conditions, curing methods, salinity and seawater compositions. The combination of seawater
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14 382 attack and ongoing hydration leads to inconsistent findings in the published literature. To
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16 383 improve the experimental study, another set of freshwater-exposed specimens should be
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18 384 included so that the strength variation caused by hydration in seawater and freshwater can be
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20 385 compared.

21 386 *4.2. Mass change*

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23 387 Mass change is another property commonly used to assess the deterioration of cementitious
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25 388 materials. The mass can vary during seawater attack due to the generation of corrosive products
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27 389 and the dissolution of hydrate phases.

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31 390 Figure 5 depicts the mass change of OPC, PBC and AAM during seawater attack. The exposure
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33 391 durations are normalized to the final test durations to better illustrate the mass variations.
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36 392 Several studies [93, 100, 102, 108] show that the mass change is two-stage process, with the
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38 393 first mass-increasing stage and the later mass-decreasing stage. Mangi et al. [100] found a mass
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40 394 increase of 0.9%–2.6% after 56 days, while the mass change fell to 0.3%–0.4% after 90 days.
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43 395 Liu et al. [102] showed that mass-increasing and mass-decreasing stages occurred at 0–60 days
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45 396 and 60–90 days respectively. Mangi et al. [93] reported that the highest mass gain was 2% and
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48 397 the mass-decreasing stage began after 30 days. The mass-increasing stage was caused by the
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51 398 formation of Friedel's salt, ettringite and gypsum within the pores. The hydration of
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53 399 cementitious materials also released more C-S-H that increased the mass. In the mass-
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55 400 decreasing stage, however, over-accumulation of these products caused expansion and
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58 401 cracking. The mass loss was also ascribed to the leaching of C-S-H and AFm phases.

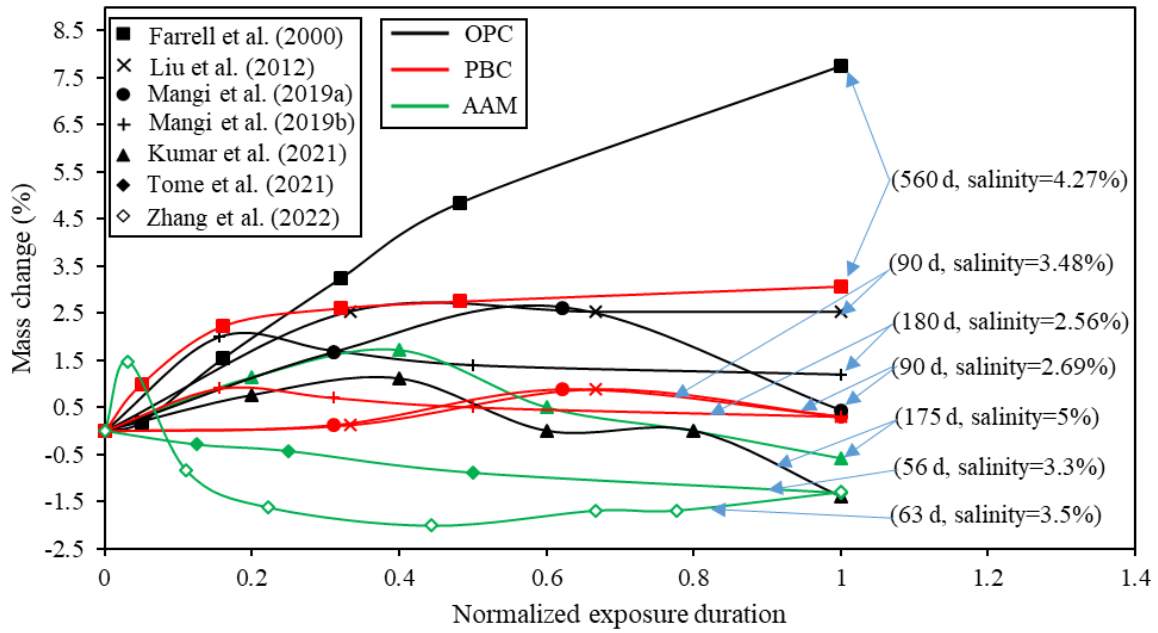


Figure 5. Mass change of cementitious materials exposed to seawater attack (data adapted from [93, 95, 100, 102, 108-110])

Some studies [95, 109, 110] have found distinct patterns of mass change during seawater attack. O'Farrell et al. [95] observed mass increase throughout the exposure period, with the greatest value of 7.8% at 560 days. The study used high strength concrete with 78 MPa grade, which could withstand greater stress caused by formation of more expansive products. Tome et al. [109] showed that lower strength concrete (24 MPa grade) exhibited mass loss throughout test period. The mass loss was due to salt crystallization damage and debris loss of the specimens. Besides, Zhang et al. [110] reported a mass-constant stage following the mass-decreasing stage. The mass-constant stage was due to the exhaustion of reactants in seawater towards the end of the test. Besides, the increase in salinity of seawater also resulted in greater extent of mass variation due to the accelerated seawater reactions.

PBC [93, 95, 100, 102] and AAM [108-110] generally have lower mass variation during seawater attack than OPC. The hydrations of PBC and AAM produce more C-S-H and C-A-S-H, which compacts the pore structure and enhances the seawater resistance. The lack of CH in

418 PBC and AAM lowers their reactivity with seawater, resulting in fewer products that cause
 419 mass change. Pozzolanic materials are often finer than OPC, which provides filling effects to
 420 reduce porosity and hence seawater intrusion.

421 Although mass change has been widely used to evaluate seawater resistance of cementitious
 422 materials, its reliability remains controversial because mass change is also caused by water
 423 absorption and hydration. It is suggested that other properties such as strength, porosity and
 424 permeability should be investigated.

425 4.3. Porosity and water absorption

426 Porosity (n) is the ratio of void to total volume of material. Water absorption (WA) is the
 427 capability of material to hold water. Both porosity and water absorption can be used to assess
 428 the resistance of cementitious materials to seawater penetration. Previous section shows that
 429 seawater attack causes mass change due to the development of expansive products and change
 430 in hydrate phases, indicating pore structure alteration. As such, the effect of seawater exposure
 431 on the porosity and water absorption of OPC, PBC and AAM is determined as shown in Table
 432 2. The porosity and water absorption in seawater environment (n_{seawater} , WA_{seawater}) are
 433 normalized to those in freshwater environment ($n_{\text{freshwater}}$, $WA_{\text{freshwater}}$).

434 **Table 2. Porosity and water absorption of cementitious materials under seawater attack**

Literature	Exposure duration (days)	Cementitious materials	Normalized porosity ($n_{\text{seawater}}/n_{\text{freshwater}}$)	Normalized water absorption ($WA_{\text{seawater}}/WA_{\text{freshwater}}$)
Binici et al. [91]	28	OPC	N.D.	0.92
		PBC	N.D.	0.71
Mengasini et al. [98]	56	OPC	0.99	N.D.
		AMM	0.85	N.D.
Puertas et al. [83]	90	AMM	0.83	N.D.
Abdel Rahman and Younes [92]	180	PBC	1.39	N.D.
Ganjian and Pouya [103]	180	OPC	N.D.	0.41
		PBC	N.D.	0.96
Memon et al. [104]	180	OPC	0.9	N.D.
		PBC	0.8	N.D.

η_{seawater} – porosity in seawater; $\eta_{\text{freshwater}}$ – porosity in freshwater

WA_{seawater} – water absorption in seawater; $WA_{\text{freshwater}}$ – water absorption in freshwater

N.D. – Not determined

435

436 Table 2 shows that porosity and water absorption are lower in seawater environment than in
 437 freshwater environment [83, 91, 98, 103, 104, 106]. Puertas et al. [83] found that the porosity
 438 of AAM exposed to seawater was 17% lower than that in freshwater. Memon et al. [104]
 439 showed that 180-day seawater attack lowered the concrete porosity by 10%–20%. The water
 440 absorption of OPC and SF concrete also reduced by 4%–59% after 180 days of seawater
 441 exposure [103]. Seawater ions such as Cl^- , SO_4^{2-} , Na^+ and Ca^{2+} can accelerate the hydration of
 442 tri-calcium silicate in cement, promoting formation of hydrate to fill the pore [106]. The
 443 precipitation of seawater salts also reduced the porosity. However, Abdel Rahman and Younes
 444 [92] found that after 180 days of seawater attack, the porosity of ceramic waste powder paste
 445 increased by 39%. The over-accumulation of seawater reaction products could enlarge the pore
 446 size and cause cracking.

447 PBC and AAM generally exhibit greater porosity reduction than OPC. The use of PBC and
 448 AAM improves the mechanical resistance, which allows for the accumulation of greater
 449 quantities of expansive products. The leaching of CH caused by seawater in PBC and AAM is
 450 also lower than in OPC [92]. The hydration of PBC and AAM can reduce the permeability of
 451 concrete by nearly 3 times [96]. In short, PBC and AMM are more resistant to seawater attack
 452 in terms of porosity and water absorption than OPC.

453 In comparison to compressive strength and mass change, relatively few studies on porosity and
 454 water absorption have been conducted, because they are typically regarded as secondary post-
 455 deterioration properties. However, in actual environment, porosity variation during the
 456 seawater exposure period is crucial in evaluating the intrusion and deterioration mechanisms,
 457 necessitating further research.

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458 4.4. Chloride permeability

459 The exposure of cementitious materials to seawater leads to chloride penetration. The chloride
460 penetration resistance is determined by chloride permeability and chloride binding capacity.

461 Chloride permeability is governed by porosity and pore size distribution. Chloride binding
462 capacity is attributed to the immobilization of free chloride in terms of Friedel's salt, which has
463 been covered in Section 3. This section therefore assesses the effect of seawater attack on
464 chloride permeability.

465 Several methods are used to determine chloride permeability, which include rapid chloride
466 permeability test (RCPT), rapid migration test (RMT) and chloride profile test (CPT). Figure
467 6 depicts the variation of chloride permeability with respect to seawater exposure durations for
468 OPC, PBC and AAM. The chloride permeability generally decreases with exposure duration.
469 Ibrahim et al. [105] showed that when exposure period was increased from 7 to 180 days, the
470 chloride permeability decreased by 40%. Ramachandran et al. [107] demonstrated that the
471 chloride permeability decreased by 28%–63% after 365-day seawater exposure. The reductions
472 in chloride permeability with exposure time were ascribed to the ongoing hydration that
473 densified the pore structure. The precipitation of chloride salts such as calcium chloride and
474 Friedel's salt also reduced the chloride permeability [97]. The formation of ettringite and
475 gypsum products from sulphate reactions suppressed the chloride diffusion [106]. Despite the
476 decreased chloride permeability, Seleem et al. [96] found that after 6-month seawater attack,
477 the maximum chloride content in concrete increased from 0.1% to 0.5%. This chloride content
478 exceeded the 0.15% threshold level, which might trigger corrosion in reinforced concrete.

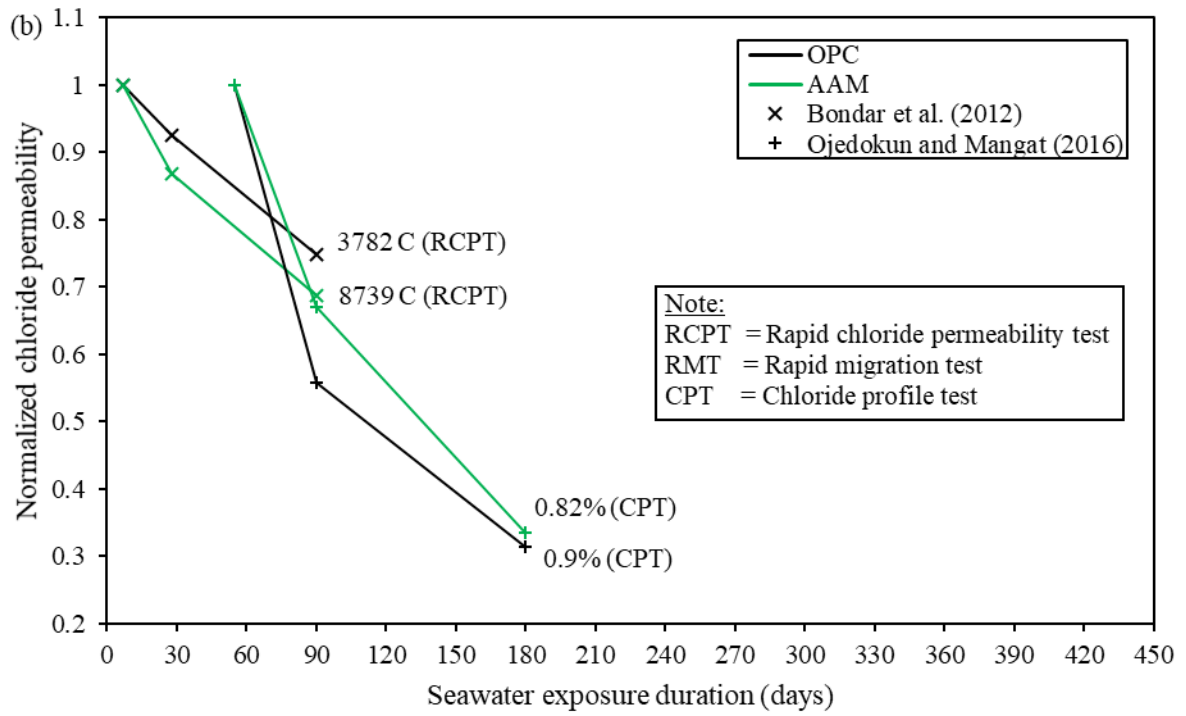
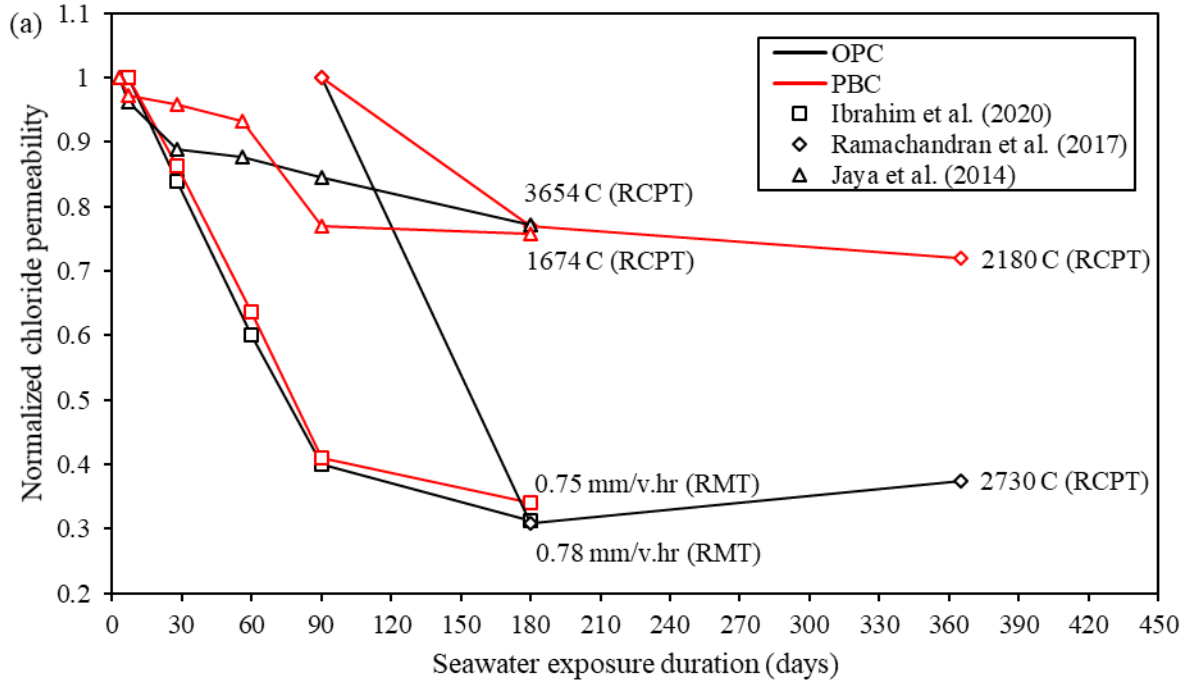


Figure 6. Chloride permeability of OPC, PBC and AAM exposed to seawater environment (data adapted from [97, 105, 107, 111, 112])

Figure 6 also presents the chloride permeability of cementitious materials at the end of each exposure period. Although seawater reduces the chloride permeability of PBC and AAM to

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485 lesser extent, their permeability remains lower than that of OPC. For instance, the use of rice
486 husk ash (RHA) reduced the chloride permeability by half [97]. OPC concrete showed
487 moderate chloride permeability, whereas FA concrete had very low permeability that was
488 equivalent to rock [107]. The 180-day chloride content was reduced from 0.9% to 0.82% after
489 OPC was replaced with AAM [112]. PBC and AAM had greater fineness and binding ability,
490 which bound free chloride and refined pore size distribution. However, Bondar et al. [111]
491 reported that the chloride permeability of AAM was two times that of OPC. This was due to
492 the use of natural pozzolans with lower reactivity in this specific study. But, thermal curing at
493 40–60°C improved the AAM by decreasing the chloride permeability to level comparable to
494 OPC. In terms of chloride permeability, the use of PBC is better way to reduce seawater attack
495 compared to OPC and AAM.

496 To summarize, the chloride permeability test is simply an assessment on the permeability of
497 cementitious materials based on chloride intrusion. This property may not accurately reflect
498 the penetration of other seawater components like sulphate and CO₂. Other tests on
499 cementitious materials, such as sorptivity and mercury intrusion porosimetry, are lacking in the
500 existing study and must be investigated further.

501 *4.5. Summary*

502 The external seawater attack influences the hardened-state properties of OPC, PBC and AAM.
503 The literature review has shown contradictory results regarding the effects of seawater on these
504 properties. The hardened-state properties can be deteriorated by seawater through mechanisms
505 such as expansive products formation, salt crystallization and hydrate dissolution. On the other
506 hand, seawater has positive effects on cementitious materials such as pore densification and
507 accelerated hydration. In this context, the assessment on these hardened-state properties could
508 not fully reflect the seawater-induced deterioration mechanism. Seawater attacks the
509 cementitious materials at the surface and propagates into the inner core, causing deterioration

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510 of varying severity along the intrusion path. Hence, future research should investigate this non-
511 uniform and progressive damage caused by seawater. One possible approach is to assess the
512 profile of deterioration products such as chloride, sulphate and CO₂, and then correlate the
513 results with mechanical properties such as stress-strain response.

514 **5. Seawater attack in combination with environmental factors**

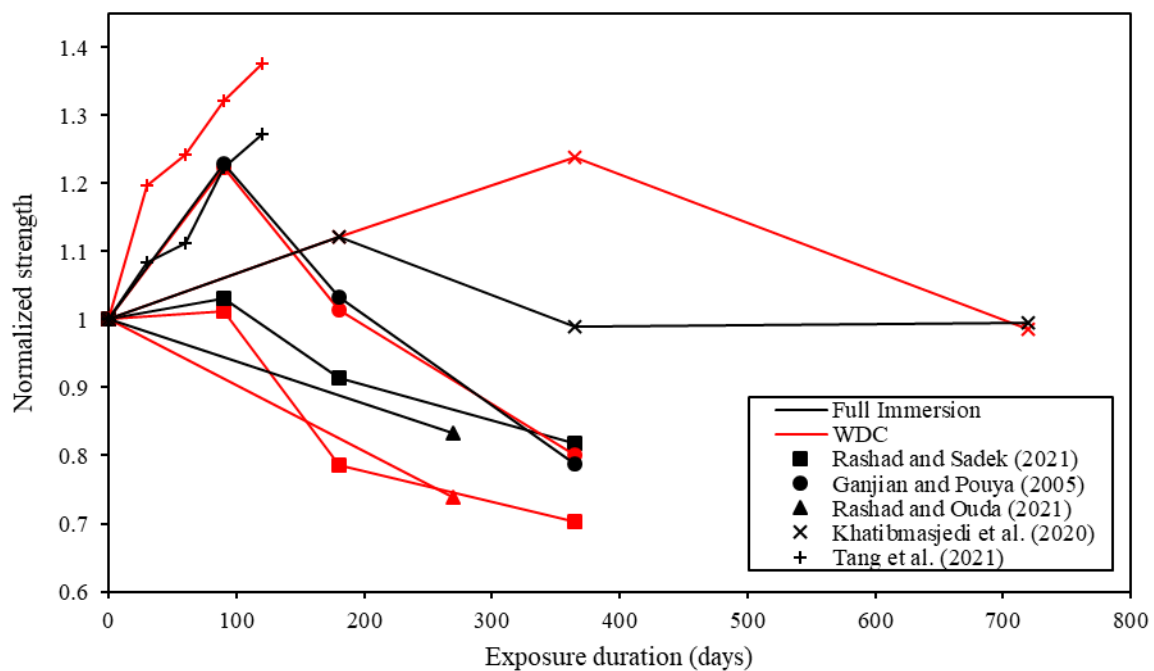
515 In practice, seawater attack is often accompanied by environmental factors such as wetting-
516 drying cycle, external service loading and temperature, which can alter the deterioration
517 mechanisms. The laboratory test involving only seawater immersion may not adequately
518 represent actual deterioration. This section looks into the effects of environmental factors.

519 *5.1. Wetting-drying cycle*

520 Seawater exposure in marine environment is divided into four zones, which are atmospheric,
521 submerged, tidal and splash zones [84, 113]. Submerged zone causes constant seawater
522 immersion of structure below sea level. The structure in atmospheric zone is exposed to
523 seawater aerosol. The rise and fall of seawater level in tidal zone and the wave action in splash
524 zone cause periodic exposure of seawater, resulting in wetting-drying cycle (WDC). The WDC
525 promotes moisture transfer and increases ion transport within the porous medium, which
526 aggravates seawater attack.

527 Figure 7 compares the effects of WDC and full immersion on the strength deterioration of
528 concrete over seawater exposure time. The WDC amplifies the deterioration effects when
529 compared to seawater immersion. Rashad and Sadek [84] showed that the strength degradation
530 in WDC test was 2%–13% higher than that in full immersion test at 365 days. Rashad and Ouda
531 [14] reported that WDC decreased concrete strength by 9.3% more than full immersion after
532 270-day seawater attack. The WDC exacerbated seawater attack by hastening ettringite and
533 gypsum formations and hydrate dissolution. The damage was also induced by the precipitation

534 of salt from seawater such as $MgSO_4 \cdot nH_2O$ [99]. Na_2SO_4 salts can precipitate to form
 535 thenardite and mirabilite, imposing salt hydration pressure [114]. However, according to some
 536 studies [103, 115], both WDC and immersion tests increased strength over time due to pore
 537 filling by seawater reaction products. Despite this, a longer exposure period still led to strength
 538 reduction. Tang et al. [116] found that although the strength increased due to ettringite
 539 formation and accelerated hydration, the WDC caused pore structure loosening and formation
 540 of scattered pores larger than 100 nm. The WDC progressively eroded and abraded the surface
 541 of cementitious materials. Micro-cracks and cavity developed, and un-bonded particles were
 542 found on the cementitious matrix.



543
 544 **Figure 7. Effect of WDC and full immersion on strength of concrete exposed to seawater**
 545 **attack (data adapted from [14, 84, 103, 115, 116])**

546 The WDC accelerates the seawater intrusion by promoting moisture transfer and ion diffusion.
 547 Wu et al. [117] showed that the WDC increased the chloride content by 11.7% to 21.8% when
 548 compared to immersion test. Tang et al. [116] demonstrated that the chloride content increased

549 by 2 times. The WDC accelerated seawater intrusion through the following mechanisms: (1)
550 capillary absorption during the initial wetting phase, (2) continued inward migration during the
551 drying phase as drying occurred from outside to inside, and (3) amplified diffusion due to
552 increased concentration gradient during the subsequent wetting. As the number of WDC grew,
553 more seawater components accumulated at the surface, which enlarged the convection zone.
554 Nonetheless, the use of PBC and AAM might reduce strength deterioration and seawater
555 intrusion by providing nucleation, filler and packing effects on cementitious matrix [14, 84].

556 5.2. External loading

557 Structure in service is subjected to loadings such as compression, tension and flexure, which
558 causes stress-strain response that alters pore structure and affects seawater intrusion.

559 Several studies [118-120] have investigated the influence of compressive loading on chloride
560 penetration. Compressive loading decreases chloride penetration at low stress level while
561 increasing it at high stress level. Bao and Wang [118] found 4% reduction in chloride
562 penetration at stress ratio of 0.3, but 40% increase in penetration at stress ratio of 0.5. Li et al.
563 [119] reported 34.7% drop in diffusivity at stress ratio of 0.6, but 46.1% rise in diffusivity at
564 stress ratio of 0.8. Kim et al. [120] observed 7.7% decrease in permeability at stress ratio of
565 0.3, but 27.2% increase in permeability at stress ratio 0.6. The reduction in chloride penetration
566 was due to closing of capillary pores under compression that reduced porosity. But, as the load
567 exceeded the critical stress, concrete suffered irreversible damage and cracks formed. The
568 compressive damage increased the width of material interfacial transition zone and chloride
569 penetration.

570 Tensile and flexural loadings have greater impact on increasing the seawater intrusion. Li et al.
571 [119] showed that the chloride penetration increased with tensile stress level, reaching
572 maximum increase of 67.5% at stress ratio of 0.7. Yoo and Kwon [121] found that tensile

1 573 loading resulted in 12.1%–33.9% greater chloride penetration than compressive loading.
2
3 574 Cementitious material was intrinsically brittle and had lower tensile resistance than
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5 575 compression. The tensile stress also increased the pore size and caused cracking. Macro-cracks
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7 576 started to develop when tensile stress ratio exceeded 0.3 [120, 122]. The increase in seawater
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9 577 penetration depended on width, length and number of cracks. Seawater can accumulate near
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11 578 crack tips, which amplifies ion diffusion [123]. In addition, external loads in case of cyclic
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13 579 loading resulted in more prominent effects by causing stiffness degradation, fatigue cracking
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15 580 and creeping [124, 125].
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20 581 *5.3. Temperature*

22 582 In actual environment, structure is exposed to temperature fluctuation due to seasonal and
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24 583 diurnal cycles. During the daytime, the temperature can vary from 30°C to 40°C [126]. The
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26 584 temperature has significant impacts on seawater penetration. Farahani et al. [127] showed that
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28 585 the chloride diffusivity in tidal zone increased by 23.5%–41.6% when temperature increased
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30 586 from 29°C to 34°C. Dousti et al. [128] found that the penetrated chloride concentration
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32 587 increased by twofold as temperature grew from 23°C to 50°C. According to Wang and Ueda
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34 588 [129], the chloride convection zone was expanded by 1.5 times when temperature increased
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36 589 from 23°C to 40°C. Chloride transport was hastened due to the increased diffusion kinetics and
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38 590 faster molecular speed at high temperature. Since the thermal gradient was in the same direction
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40 591 to concentration gradient, the heat flux facilitated the diffusion. The increased temperature also
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42 592 reduced the chloride binding capacity of hydrate phase, decomposing Friedel's salt to release
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44 593 chloride under greater thermal vibration [129]. In addition, the cyclic heating-cooling
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46 594 environment caused drying shrinkage damage [103]. The precipitation of salts, such as
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48 595 $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$, $\text{MgSO}_4 \cdot \text{H}_2\text{O}$ and $\text{MgSO}_4 \cdot 6\text{H}_2\text{O}$, induced salt crystallization pressure [130,
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597 5.4. *Summary*

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2 598 Seawater attack is aggravated by environmental factors such as WDC, external loading and
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5 599 temperature. WDC accelerates seawater intrusion and the reactions with cementitious materials.
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7 600 External loading alters pore structure of cementitious matrix, facilitating the penetration of
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10 601 corrosive ions. Elevated temperature induces thermal gradient and increases diffusion kinetics,
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12 602 which promotes seawater ingress. Although the existing studies have reproduced various
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14 603 environmental site conditions in the experiment, their accuracy has not been validated. The
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17 604 outcomes may be imprecise for practical application. Further research is needed to establish
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19 605 correlation between deterioration in laboratory test conditions and actual environments.
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23 606 **6. Discussions and perspectives**

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25 607 In the midst of sea-level-rise crisis, cementitious materials are at risk of premature deterioration
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27 608 due to the intensified seawater attack. Designers and engineers must therefore reassess the
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30 609 durability performance of existing structures; in the worse scenario, reconstruction and
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32 610 rehabilitation are required to ensure compliance with functional requirement standards, which
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35 611 can eventually increase the life-cycle cost. Cementitious materials with more hydrates and less
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37 612 reactants, such as PBC and AAM, offer excellent seawater resistance. They can thus be utilized
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40 613 as protective surface coating on structures to reduce capillary absorption while also acting as
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42 614 barrier against topographical interactions with seawater. Flowability, viscosity and adhesive
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45 615 stability of PBC and AAM can be easily controlled during coating processes like spraying,
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47 616 blading and brushing. The limitation of PBC and AAM is the low pH buffer, which is
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50 617 conducive to seawater-induced hydrate dissolution. Recent technology [132] that uses
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52 618 microcapsule containing hydroxide (OH^-) ions to replenish the CH consumed in seawater
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54 619 reactions, may be adopted.

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57 620 The external seawater attack influences the hardened-state properties of OPC, PBC and AAM.
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60 621 Due to time constraint, the long-term durability of cementitious materials has not been
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1 622 adequately researched. Most durability studies have shortened the test durations by adjusting
2 623 composition, salinity and exposure temperature in order to achieve accelerated seawater
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4 624 reactions. However, the deterioration mechanism of cementitious materials is often
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7 625 inconsistent and can vary based on parameters such as material types, grade, mixture
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9 626 proportions, permeability, as well as curing periods and methods. Furthermore, seawater attack
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11 627 can have both positive effects, such as pore densification and faster hydration, and negative
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13 628 effects, such as expansion, salt crystallization and hydrate dissolution, on the hardened-state
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15 629 properties. The accelerated tests may overestimate the durability requirements, causing the
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17 630 design and selection of cementitious materials that would have performed better and more
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19 631 effectively in the field to be overlooked. Future research can incorporate both long-term field
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21 632 tests and accelerated indoor experiments to validate the test methods and constraints.
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23 633 Computation optimizations [133] such as non-linear statistical regressions and machine
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25 634 learning algorithms can be used to establish their correlations and deliver more credible test
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27 635 result analysis and interpretation.
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34 636 Seawater attack can be exacerbated when environmental factors such as WDC, external loading
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36 637 and temperature are considered. Table 3 outlines the environmental conditions that have been
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38 638 simulated in the past studies. Researchers adopt various test methods to assess the seawater
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40 639 resistance of cementitious materials based on national standards or customized protocols,
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42 640 which are essentially developed for the study of specific degradation mechanism and laboratory
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44 641 evaluation. The outcomes may be imprecise for practical applications. Further study is needed
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46 642 to establish strong correlation between laboratory tests and actual deterioration by
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48 643 incorporating large-scale field data using methods such as real-time sensor system and
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50 644 automated integration testing [134]. The data can be used to support and develop standard
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52 645 guidelines for assessing the durability of cementitious materials in seawater environment.
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Table 3. Environmental conditions considered in laboratory tests of seawater attack

Literature	Wetting-drying cycle	External loading	Temperature	Simulated site
Rashad and Ouda [14]	Wetting: 18 hr Drying: 6 hr	-	-	Tidal zone
Rashad and Sadek [84]	Wetting: 18 hr Drying: 6 hr	-	-	Tidal zone
Farahani et al. [127]	-	-	18–35 °C	Bandar Abbas, Iran
Wu et al. [117]	Wetting: 8 hr Drying: 8 hr	-	-	Bohai Sea; East Sea; Yellow Sea
Hamzah et al. [99]	Wetting: 15 hr Drying: 9 hr	-	-	Malaysia
Jaya et al. [97]	Wetting: 15 hr Drying: 9 hr	-	-	Malaysia
Ting et al. [125]	Wetting: 12 hr Drying: 12 hr	30%–85% cyclic compression	-	Malaysia
Fraternali et al. [89]	Site condition	-	-	Port of Salerno
Ganjian and Pouya [103]	Wetting: 6 hr Drying: 6 hr	-	37–42 °C	South coast of Iran
Dousti et al. [128]	-	-	22–50 °C	South coast of Iran
Chen et al. [130]	-	56%–90% cyclic flexure	50 °C	Subtropical climate
Tang et al. [116]	Wetting: 12 hr Drying: 12 hr	-	60 °C	Zhairuoshan Island
Liu et al. [124]	Wetting: 10 hr Drying: 38 hr	20%–50% cyclic flexure	80±5 °C	-
Sahmaran et al. [131]	Wetting: 144 hr Drying: 24 hr	-	100 °C	-
Bao and Wang [118]	-	10%–50% compression	-	-
Li et al. [119]	-	20%–80% compression 18%–67.5% tension	-	-
Yoo and Kwon [121]	-	30%–60% compression/tension	-	-
Kim et al. [120]	-	30%–60% tension	-	-
Yang and Luo [122]	-	50% flexure	-	-

648

649 **7. Conclusions**

650 This study reviews the durability of OPC, PBC and AAM exposed to seawater environment in
651 the aspects of chemical interactions and hardened-state properties. The effect of environmental
652 factors including WDC, external loading and temperature on seawater attack has been
653 discussed. Based on the literature review, the following conclusions are drawn:

654 (1) When exposed to seawater, OPC, PBC and AAM deteriorate due to chemical interactions
655 with chloride, sulphate and CO₂. Seawater reactions consume and deplete the hydrate
656 phases such as C-S-H and CH, resulting in reduced binding capability, increased porosity
657 and loss of alkalinity for corrosion resistance. Although PBC and AAM are more resistant
658 to seawater attack due to the lack of CH and aluminate as reactants, their hydrates like C-
659 A-S-H and N-A-S-H have low Ca/Si ratio, making them susceptible to hydrate
660 decalcification.

661 (2) After seawater attack, the strength variation is -76% to 51.4% for OPC, -50% to 95.2% for
662 PBC and -42.1% to 62% for AAM. The mass increases at first, but decreases later. The
663 porosity, water absorption and chloride permeability reduces by 1.2% to 15.2%, 0.2% to
664 28.7% and 22.8% to 68.8% respectively. PBC and AAM minimize the degradation of the
665 hardened-state properties due to the refined pore structure, improved mechanical
666 properties and lower reactivity with seawater.

667 (3) In general, seawater attack has negative effects on hardened-state properties due to the
668 development of expansive products, salt crystallization and hydrate dissolution. Seawater,
669 on the other hand, has beneficial effects such as pore structure densification and hydration
670 acceleration. Thus, the impact of seawater on durability of cementitious materials is
671 determined by the dominance of positive or negative effects.

672 (4) Environmental factors of WDC, external loading and temperature exacerbates the seawater
673 attack. WDC hastens moisture transfer and expands water convection zone, accelerating

674 the transport of corrosive ions. External loading promotes seawater penetration by
675 increasing porosity and causing cracks; though compressive loading below the stress limit
676 can reduce seawater intrusion. The increased temperature speeds up seawater ingress by
677 inducing thermal gradient, which increases the kinetics of ion transport.

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681 **Reference**

- 682 [1] A. Adesina, *Recent advances in the concrete industry to reduce its carbon dioxide emissions*.
683 *Environmental Challenges*, 2020. **1**: p. 100004.
- 684 [2] F. Song, G. J. Zhang, V. Ramanathan and L. R. Leung, *Trends in surface equivalent potential*
685 *temperature: A more comprehensive metric for global warming and weather extremes*. *Proceedings*
686 *of the National Academy of Sciences*, 2022. **119**(6): p. e2117832119.
- 687 [3] D. T. Vu, T. Yamada and H. Ishidaira, *Assessing the impact of sea level rise due to climate change*
688 *on seawater intrusion in Mekong Delta, Vietnam*. *Water Science and Technology*, 2018. **77**(6): p. 1632-
689 1639.
- 690 [4] O. Micheal, B. Glavovic, J. Hinkel, v. Roderik, A. Magnan, A. Abd-Elgawad, C. Rongshu, M. Cifuentes,
691 D. Robert, T. Ghosh, J. Hay, M. Ben, B. Meyssignac, Z. Sebesvari, S. A.J, S. Dangendorf and T. Frederikse,
692 *Sea Level Rise and Implications for Low Lying Islands, Coasts and Communities*. 2019. p. 321-445.
- 693 [5] B. Ataie-Ashtiani, A. D. Werner, C. T. Simmons, L. K. Morgan and C. Lu, *How important is the impact*
694 *of land-surface inundation on seawater intrusion caused by sea-level rise?* *Hydrogeology Journal*, 2013.
695 **21**(7): p. 1673-1677.
- 696 [6] H. Ketabchi, D. Mahmoodzadeh, B. Ataie-Ashtiani and C. T. Simmons, *Sea-level rise impacts on*
697 *seawater intrusion in coastal aquifers: Review and integration*. *Journal of Hydrology*, 2016. **535**: p.
698 235-255.
- 699 [7] S. B. Lee, M. Li and F. Zhang, *Impact of sea level rise on tidal range in Chesapeake and Delaware*
700 *Bays*. *Journal of Geophysical Research: Oceans*, 2017. **122**(5): p. 3917-3938.
- 701 [8] F. Qu, W. Li, W. Dong, V. W. Tam and T. Yu, *Durability deterioration of concrete under marine*
702 *environment from material to structure: A critical review*. *Journal of Building Engineering*, 2021. **35**: p.
703 102074.
- 704 [9] D. Jansen, F. Goetz-Neunhoeffler, B. Lothenbach and J. Neubauer, *The early hydration of Ordinary*
705 *Portland Cement (OPC): An approach comparing measured heat flow with calculated heat flow from*
706 *QXRD*. *Cement and Concrete Research*, 2012. **42**(1): p. 134-138.
- 707 [10] J. J. Beaudoin, S. Catinaud and J. Marchand, *Volume stability of calcium hydroxide in aggressive*
708 *solutions*. *Cement and Concrete Research*, 2001. **31**(1): p. 149-151.
- 709 [11] F. U. A. Shaikh and J. Dobson, *Effect of fly ash on compressive strength and chloride binding of*
710 *seawater-mixed mortars*. *Journal of Sustainable Cement-Based Materials*, 2019. **8**(5): p. 275-289.
- 711 [12] E. Ganjian and H. S. Pouya, *The effect of Persian Gulf tidal zone exposure on durability of mixes*
712 *containing silica fume and blast furnace slag*. *Construction and Building Materials*, 2009. **23**(2): p. 644-
713 652.

- 714 [13] A. Dasar, D. Patah, H. Hamada, Y. Sagawa and D. Yamamoto, *Applicability of seawater as a mixing*
715 *and curing agent in 4-year-old concrete*. Construction and Building Materials, 2020. **259**: p. 119692.
- 716 [14] A. M. Rashad and A. S. Ouda, *Effect of tidal zone and seawater attack on high-volume fly ash*
717 *pastes enhanced with metakaolin and quartz powder in the marine environment*. Microporous and
718 Mesoporous Materials, 2021. **324**: p. 111261.
- 719 [15] J. L. Provis, *Alkali-activated materials*. Cement and Concrete Research, 2018. **114**: p. 40-48.
- 720 [16] J. L. Provis, A. Palomo and C. Shi, *Advances in understanding alkali-activated materials*. Cement
721 and Concrete Research, 2015. **78**: p. 110-125.
- 722 [17] F. J. Millero and F. Huang, *The density of seawater as a function of salinity (5 to 70 g kg⁻¹) and*
723 *temperature (273.15 to 363.15 K)*. Ocean Science, 2009. **5**(2): p. 91-100.
- 724 [18] P. Li, W. Li, Z. Sun, L. Shen and D. Sheng, *Development of sustainable concrete incorporating*
725 *seawater: A critical review on cement hydration, microstructure and mechanical strength*. Cement and
726 Concrete Composites, 2021. **121**: p. 104100.
- 727 [19] Y. Yi, D. Zhu, S. Guo, Z. Zhang and C. Shi, *A review on the deterioration and approaches to enhance*
728 *the durability of concrete in the marine environment*. Cement and Concrete Composites, 2020. **113**: p.
729 103695.
- 730 [20] K. L. Davis, M. A. Coleman, S. D. Connell, B. D. Russell, B. M. Gillanders and B. P. Kelaher, *Ecological*
731 *performance of construction materials subject to ocean climate change*. Marine environmental
732 research, 2017. **131**: p. 177-182.
- 733 [21] S. A. Mangi, A. Makhija, M. S. Raza, S. H. Khahro and A. A. Jhatial, *A comprehensive review on*
734 *effects of seawater on engineering properties of concrete*. Silicon, 2021. **13**(12): p. 4519-4526.
- 735 [22] Y. Zhao, X. Hu, C. Shi, Z. Zhang and D. Zhu, *A review on seawater sea-sand concrete: Mixture*
736 *proportion, hydration, microstructure and properties*. Construction and Building Materials, 2021. **295**:
737 p. 123602.
- 738 [23] J. Xiao, C. Qiang, A. Nanni and K. Zhang, *Use of sea-sand and seawater in concrete construction:*
739 *Current status and future opportunities*. Construction and Building Materials, 2017. **155**: p. 1101-1111.
- 740 [24] E. Samson, J. Marchand, K. A. Snyder and J. J. Beaudoin, *Modeling ion and fluid transport in*
741 *unsaturated cement systems in isothermal conditions*. Cement and Concrete Research, 2005. **35**(1): p.
742 141-153.
- 743 [25] X. Li, S. Chen, Q. Xu and Y. Xu, *Modeling the three-dimensional unsaturated water transport in*
744 *concrete at the mesoscale*. Computers & Structures, 2017. **190**: p. 61-74.
- 745 [26] S. Poyet, S. Charles, N. Honoré and V. L'Hostis, *Assessment of the unsaturated water transport*
746 *properties of an old concrete: Determination of the pore-interaction factor*. Cement and Concrete
747 Research, 2011. **41**(10): p. 1015-1023.
- 748 [27] O. Truc, J. P. Ollivier and L.-O. Nilsson, *Numerical simulation of multi-species diffusion*. Materials
749 and Structures, 2000. **33**(9): p. 566-573.
- 750 [28] E. Samson and J. Marchand, *Modeling the transport of ions in unsaturated cement-based*
751 *materials*. Computers & Structures, 2007. **85**(23-24): p. 1740-1756.
- 752 [29] E. Samson, G. Lemaire, J. Marchand and J. J. Beaudoin, *Modeling chemical activity effects in strong*
753 *ionic solutions*. Computational Materials Science, 1999. **15**(3): p. 285-294.
- 754 [30] S. Alvès, G. Demouchy, A. Bee, D. Talbot, A. Bourdon and A. M. F. Neto, *Investigation of the sign*
755 *of the Soret coefficient in different ionic and surfacted magnetic colloids using forced Rayleigh*
756 *scattering and single-beam Z-scan techniques*. Philosophical Magazine, 2003. **83**(17-18): p. 2059-2066.
- 757 [31] E. Samson and J. Marchand, *Modeling the effect of temperature on ionic transport in cementitious*
758 *materials*. Cement and Concrete Research, 2007. **37**(3): p. 455-468.
- 759 [32] A. Suryavanshi, J. Scantlebury and S. Lyon, *Mechanism of Friedel's salt formation in cements rich*
760 *in tri-calcium aluminate*. Cement and concrete research, 1996. **26**(5): p. 717-727.
- 761 [33] T. Matschei, B. Lothenbach and F. Glasser, *The AFm phase in Portland cement*. Cement and
762 concrete research, 2007. **37**(2): p. 118-130.
- 763 [34] K. De Weerd, H. Justnes and M. R. Geiker, *Changes in the phase assemblage of concrete exposed*
764 *to sea water*. Cement and Concrete Composites, 2014. **47**: p. 53-63.

- 765 [35] A. Mesbah, M. François, C. Cau-dit-Coumes, F. Frizon, Y. Filinchuk, F. Leroux, J. Ravaux and G.
766 Renaudin, *Crystal structure of Kuzel's salt $3CaO \cdot Al_2O_3 \cdot 1/2CaSO_4 \cdot 1/2CaCl_2 \cdot 11H_2O$ determined by*
767 *synchrotron powder diffraction*. Cement and Concrete Research, 2011. **41**(5): p. 504-509.
- 768 [36] P. Li, W. Li, T. Yu, F. Qu and V. W. Tam, *Investigation on early-age hydration, mechanical properties*
769 *and microstructure of seawater sea sand cement mortar*. Construction and Building Materials, 2020.
770 **249**: p. 118776.
- 771 [37] T. U. Mohammed, H. Hamada and T. Yamaji, *Performance of seawater-mixed concrete in the tidal*
772 *environment*. Cement and concrete research, 2004. **34**(4): p. 593-601.
- 773 [38] E. Ariyachandra, S. Peethamparan, S. Patel and A. Orlov, *Chloride diffusion and binding in concrete*
774 *containing NO₂ sequestered recycled concrete aggregates (NRCAs)*. Construction and Building
775 Materials, 2021. **291**: p. 123328.
- 776 [39] C. Qiao, P. Suraneni, T. N. W. Ying, A. Choudhary and J. Weiss, *Chloride binding of cement pastes*
777 *with fly ash exposed to CaCl₂ solutions at 5 and 23° C*. Cement and Concrete Composites, 2019. **97**: p.
778 43-53.
- 779 [40] P. Suraneni, V. J. Azad, B. O. Isgor and W. J. Weiss, *Calcium oxychloride formation in pastes*
780 *containing supplementary cementitious materials: Thoughts on the role of cement and supplementary*
781 *cementitious materials reactivity*. RILEM Technical Letters, 2016. **1**: p. 24-30.
- 782 [41] H. E. Álava, N. De Belie and G. De Schutter, *Proposed mechanism for the formation of oxychloride*
783 *crystals during sodium chloride application as a deicer salt in carbonated concrete*. Construction and
784 Building Materials, 2016. **109**: p. 188-197.
- 785 [42] C. Qiao, P. Suraneni and J. Weiss, *Flexural strength reduction of cement pastes exposed to CaCl₂*
786 *solutions*. Cement and Concrete Composites, 2018. **86**: p. 297-305.
- 787 [43] C. Qiao, P. Suraneni, M. Tsui Chang and J. Weiss, *Damage in cement pastes exposed to MgCl₂*
788 *solutions*. Materials and Structures, 2018. **51**(3): p. 1-15.
- 789 [44] M. Nehdi and M. Hayek, *Behavior of blended cement mortars exposed to sulfate solutions cycling*
790 *in relative humidity*. Cement and Concrete Research, 2005. **35**(4): p. 731-742.
- 791 [45] P. J. Tikalsky, D. Roy, B. Scheetz and T. Krize, *Redefining cement characteristics for sulfate-resistant*
792 *Portland cement*. Cement and Concrete Research, 2002. **32**(8): p. 1239-1246.
- 793 [46] U. H. Jakobsen, K. De Weerd and M. R. Geiker, *Elemental zonation in marine concrete*. Cement
794 and Concrete Research, 2016. **85**: p. 12-27.
- 795 [47] K. De Weerd and H. Justnes, *The effect of sea water on the phase assemblage of hydrated cement*
796 *paste*. Cement and Concrete Composites, 2015. **55**: p. 215-222.
- 797 [48] T. Aye and C. T. Oguchi, *Resistance of plain and blended cement mortars exposed to severe sulfate*
798 *attacks*. Construction and Building Materials, 2011. **25**(6): p. 2988-2996.
- 799 [49] S. Yoon, J. Ha, S. R. Chae, D. A. Kilcoyne, Y. Jun, J. E. Oh and P. J. Monteiro, *Phase changes of*
800 *monosulfoaluminate in NaCl aqueous solution*. Materials, 2016. **9**(5): p. 401.
- 801 [50] O. S. B. Al-Amoudi, M. Maslehuddin and Y. A. Abdul-Al, *Role of chloride ions on expansion and*
802 *strength reduction in plain and blended cements in sulfate environments*. Construction and Building
803 Materials, 1995. **9**(1): p. 25-33.
- 804 [51] Y. Cao, L. Guo, B. Chen and J. Wu, *Thermodynamic modelling and experimental investigation on*
805 *chloride binding in cement exposed to chloride and chloride-sulfate solution*. Construction and Building
806 Materials, 2020. **246**: p. 118398.
- 807 [52] M. Frías, S. Goñi, R. García and R. V. de La Villa, *Seawater effect on durability of ternary cements.*
808 *Synergy of chloride and sulphate ions*. Composites Part B: Engineering, 2013. **46**: p. 173-178.
- 809 [53] K. Samimi, S. Kamali-Bernard and A. A. Maghsoudi, *Durability of self-compacting concrete*
810 *containing pumice and zeolite against acid attack, carbonation and marine environment*. Construction
811 and building materials, 2018. **165**: p. 247-263.
- 812 [54] C.-F. Chang and J.-W. Chen, *The experimental investigation of concrete carbonation depth*.
813 Cement and Concrete Research, 2006. **36**(9): p. 1760-1767.

- 814 [55] M. Saillio, V. Baroghel-Bouny and F. Barberon, *Chloride binding in sound and carbonated*
1 815 *cementitious materials with various types of binder*. Construction and Building Materials, 2014. **68**: p.
2 816 82-91.
- 3 817 [56] H. Chang, P. Feng, K. Lyu and J. Liu, *A novel method for assessing CSH chloride adsorption in cement*
4 818 *pastes*. Construction and Building Materials, 2019. **225**: p. 324-331.
- 5 819 [57] H. Ye, X. Jin, C. Fu, N. Jin, Y. Xu and T. Huang, *Chloride penetration in concrete exposed to cyclic*
6 820 *drying-wetting and carbonation*. Construction and Building Materials, 2016. **112**: p. 457-463.
- 7 821 [58] T. Sibbick, D. Fenn and N. Crammond, *The occurrence of thaumasite as a product of seawater*
8 822 *attack*. Cement and Concrete Composites, 2003. **25**(8): p. 1059-1066.
- 9 823 [59] J. Bensted, *Thaumasite—background and nature in deterioration of cements, mortars and*
10 824 *concretes*. Cement and Concrete Composites, 1999. **21**(2): p. 117-121.
- 11 825 [60] M. Anwar and D. A. Emarah, *Resistance of concrete containing ternary cementitious blends to*
12 826 *chloride attack and carbonation*. Journal of Materials Research and Technology, 2020. **9**(3): p. 3198-
13 827 3207.
- 14 828 [61] B. Lothenbach, K. Scrivener and R. Hooton, *Supplementary cementitious materials*. Cement and
15 829 *concrete research*, 2011. **41**(12): p. 1244-1256.
- 16 830 [62] M. M. A. Elahi, C. R. Shearer, A. N. R. Reza, A. K. Saha, M. N. N. Khan, M. M. Hossain and P. K.
17 831 *Sarker, Improving the sulfate attack resistance of concrete by using supplementary cementitious*
18 832 *materials (SCMs): A review*. Construction and Building Materials, 2021. **281**: p. 122628.
- 19 833 [63] F. Nosouhian, M. Fincan, N. Shanahan, Y. P. Stetsko, K. A. Riding and A. Zayed, *Effects of slag*
20 834 *characteristics on sulfate durability of Portland cement-slag blended systems*. Construction and
21 835 *Building Materials*, 2019. **229**: p. 116882.
- 22 836 [64] S. Ogawa, T. Nozaki, K. Yamada, H. Hirao and R. Hooton, *Improvement on sulfate resistance of*
23 837 *blended cement with high alumina slag*. Cement and Concrete Research, 2012. **42**(2): p. 244-251.
- 24 838 [65] Y. Wang, S. Nanukuttan, Y. Bai and P. Basheer, *Influence of combined carbonation and chloride*
25 839 *ingress regimes on rate of ingress and redistribution of chlorides in concretes*. Construction and
26 840 *Building Materials*, 2017. **140**: p. 173-183.
- 27 841 [66] M. Saillio, V. Baroghel-Bouny, S. Pradelle, M. Bertin, J. Vincent and J.-B. d. E. de Lacaillerie, *Effect*
28 842 *of supplementary cementitious materials on carbonation of cement pastes*. Cement and concrete
29 843 *research*, 2021. **142**: p. 106358.
- 30 844 [67] I. Ismail, S. A. Bernal, J. L. Provis, R. San Nicolas, D. G. Brice, A. R. Kilcullen, S. Hamdan and J. S. van
31 845 *Deventer, Influence of fly ash on the water and chloride permeability of alkali-activated slag mortars*
32 846 *and concretes*. Construction and Building Materials, 2013. **48**: p. 1187-1201.
- 33 847 [68] I. Ismail, S. A. Bernal, J. L. Provis, R. San Nicolas, S. Hamdan and J. S. van Deventer, *Modification*
34 848 *of phase evolution in alkali-activated blast furnace slag by the incorporation of fly ash*. Cement and
35 849 *Concrete Composites*, 2014. **45**: p. 125-135.
- 36 850 [69] O. Kayali, M. Khan and M. S. Ahmed, *The role of hydrotalcite in chloride binding and corrosion*
37 851 *protection in concretes with ground granulated blast furnace slag*. Cement and Concrete Composites,
38 852 2012. **34**(8): p. 936-945.
- 39 853 [70] M. Khan, O. Kayali and U. Troitzsch, *Chloride binding capacity of hydrotalcite and the competition*
40 854 *with carbonates in ground granulated blast furnace slag concrete*. Materials and Structures, 2016.
41 855 **49**(11): p. 4609-4619.
- 42 856 [71] X. Ke, S. A. Bernal and J. L. Provis, *Uptake of chloride and carbonate by Mg-Al and Ca-Al layered*
43 857 *double hydroxides in simulated pore solutions of alkali-activated slag cement*. Cement and Concrete
44 858 *Research*, 2017. **100**: p. 1-13.
- 45 859 [72] T. Bakharev, J. G. Sanjayan and Y.-B. Cheng, *Sulfate attack on alkali-activated slag concrete*.
46 860 *Cement and Concrete research*, 2002. **32**(2): p. 211-216.
- 47 861 [73] H. Ye, Z. Chen and L. Huang, *Mechanism of sulfate attack on alkali-activated slag: The role of*
48 862 *activator composition*. Cement and Concrete Research, 2019. **125**: p. 105868.
- 49 863 [74] M. Komljenović, Z. Baščarević, N. Marjanović and V. Nikolić, *External sulfate attack on alkali-*
50 864 *activated slag*. Construction and Building Materials, 2013. **49**: p. 31-39.

- 865 [75] I. Ismail, S. A. Bernal, J. L. Provis, S. Hamdan and J. S. van Deventer, *Microstructural changes in*
1 866 *alkali activated fly ash/slag geopolymers with sulfate exposure*. *Materials and structures*, 2013. **46**(3):
2 867 p. 361-373.
- 3 868 [76] F. Puertas, M. Palacios and T. Vázquez, *Carbonation process of alkali-activated slag mortars*.
4 869 *Journal of materials science*, 2006. **41**(10): p. 3071-3082.
- 5 870 [77] T. Bakharev, J. Sanjayan and Y.-B. Cheng, *Resistance of alkali-activated slag concrete to*
6 871 *carbonation*. *Cement and Concrete Research*, 2001. **31**(9): p. 1277-1283.
- 7 872 [78] R. Pouhet and M. Cyr, *Carbonation in the pore solution of metakaolin-based geopolymer*. *Cement*
8 873 *and Concrete Research*, 2016. **88**: p. 227-235.
- 9 874 [79] S. A. Bernal, J. L. Provis, B. Walkley, R. San Nicolas, J. D. Gehman, D. G. Brice, A. R. Kilcullen, P.
10 875 Duxson and J. S. van Deventer, *Gel nanostructure in alkali-activated binders based on slag and fly ash,*
11 876 *and effects of accelerated carbonation*. *Cement and Concrete Research*, 2013. **53**: p. 127-144.
- 12 877 [80] J. Zhang, C. Shi, Z. Zhang and Z. Ou, *Durability of alkali-activated materials in aggressive*
13 878 *environments: A review on recent studies*. *Construction and Building Materials*, 2017. **152**: p. 598-613.
- 14 879 [81] S. A. Bernal, R. San Nicolas, R. J. Myers, R. M. de Gutiérrez, F. Puertas, J. S. van Deventer and J. L.
15 880 Provis, *MgO content of slag controls phase evolution and structural changes induced by accelerated*
16 881 *carbonation in alkali-activated binders*. *Cement and Concrete Research*, 2014. **57**: p. 33-43.
- 17 882 [82] H. Yiğiter, H. Yazıcı and S. Aydın, *Effects of cement type, water/cement ratio and cement content*
18 883 *on sea water resistance of concrete*. *Building and environment*, 2007. **42**(4): p. 1770-1776.
- 19 884 [83] F. Puertas, R. Gutierrez, A. Fernández-Jiménez, S. Delvasto and J. Maldonado, *Alkaline cement*
20 885 *mortars. Chemical resistance to sulfate and seawater attack*. *Materiales de Construcción*, 2002.
21 886 **52**(267): p. 55-71.
- 22 887 [84] A. M. Rashad and D. M. Sadek, *An Exploratory Study on Alkali-Activated Slag Blended with*
23 888 *Microsize Metakaolin Particles Under the Effect of Seawater Attack and Tidal Zone*. *Arabian Journal*
24 889 *for Science and Engineering*, 2021: p. 1-12.
- 25 890 [85] A. M. Rashad, A. S. Ouda and D. M. Sadek, *Behavior of alkali-activated metakaolin pastes blended*
26 891 *with quartz powder exposed to seawater attack*. *Journal of Materials in Civil Engineering*, 2018. **30**(8):
27 892 p. 04018159.
- 28 893 [86] A. Palomo, M. T. Blanco-Varela, M. Granizo, F. Puertas, T. Vazquez and M. Grutzeck, *Chemical*
29 894 *stability of cementitious materials based on metakaolin*. *Cement and Concrete research*, 1999. **29**(7):
30 895 p. 997-1004.
- 31 896 [87] A. Fernández-Jiménez, I. Garcia-Lodeiro and A. Palomo, *Durability of alkali-activated fly ash*
32 897 *cementitious materials*. *Journal of Materials Science*, 2007. **42**(9): p. 3055-3065.
- 33 898 [88] F. M. Wegian, *Effect of seawater for mixing and curing on structural concrete*. *The IES Journal Part*
34 899 *A: Civil & Structural Engineering*, 2010. **3**(4): p. 235-243.
- 35 900 [89] F. Fraternali, S. Spadea and V. P. Berardi, *Effects of recycled PET fibres on the mechanical*
36 901 *properties and seawater curing of Portland cement-based concretes*. *Construction and Building*
37 902 *Materials*, 2014. **61**: p. 293-302.
- 38 903 [90] S. Kumar, *Influence of water quality on the strength of plain and blended cement concretes in*
39 904 *marine environments*. *Cement and Concrete Research*, 2000. **30**(3): p. 345-350.
- 40 905 [91] H. Binici, O. Aksogan, E. B. Görür, H. Kaplan and M. N. Bodur, *Performance of ground blast furnace*
41 906 *slag and ground basaltic pumice concrete against seawater attack*. *Construction and Building*
42 907 *Materials*, 2008. **22**(7): p. 1515-1526.
- 43 908 [92] H. A. Abdel Rahman and M. M. Younes, *Performance of irradiated blended cement paste*
44 909 *composites containing ceramic waste powder towards sulfates, chlorides, and seawater attack*.
45 910 *Journal of Vinyl and Additive Technology*, 2020. **26**(1): p. 24-34.
- 46 911 [93] S. A. Mangi, M. H. W. Ibrahim, N. Jamaluddin, M. F. Arshad and S. Shahidan, *Performances of*
47 912 *concrete containing coal bottom ash with different fineness as a supplementary cementitious material*
48 913 *exposed to seawater*. *Engineering Science and Technology, an International Journal*, 2019. **22**(3): p.
49 914 929-938.

- 915 [94] N. Zhang, H. Li, D. Peng and X. Liu, *Properties evaluation of silica-alumina based concrete: durability and environmental friendly performance*. Construction and Building Materials, 2016. **115**: p. 105-113.
- 916
917
- 918 [95] M. O'Farrell, S. Wild and B. Sabir, *Resistance to chemical attack of ground brick-PC mortar: Part II. Synthetic seawater*. Cement and Concrete Research, 2000. **30**(5): p. 757-765.
- 919
920 [96] H. E.-D. H. Seleem, A. M. Rashad and B. A. El-Sabbagh, *Durability and strength evaluation of high-performance concrete in marine structures*. Construction and Building Materials, 2010. **24**(6): p. 878-884.
- 921
922
- 923 [97] R. P. Jaya, B. H. A. Bakar, M. A. M. Johari, M. H. W. Ibrahim, M. R. Hainin and D. S. Jayanti, *Strength and microstructure analysis of concrete containing rice husk ash under seawater attack by wetting and drying cycles*. Advances in cement research, 2014. **26**(3): p. 145-154.
- 924
925
- 926 [98] L. Mengasini, M. Mavroulidou and M. J. Gunn, *Alkali-activated concrete mixes with ground granulated blast furnace slag and paper sludge ash in seawater environments*. Sustainable Chemistry and Pharmacy, 2021. **20**: p. 100380.
- 927
928
- 929 [99] A. Hamzah, M. W. Ibrahim and E. Manan. *Carbonation and strength of self-compacting concrete with coal bottom ash exposed to seawater by wetting-drying cycle*. in *IOP Conference Series: Earth and Environmental Science*. 2020. IOP Publishing.
- 930
931
- 932 [100] S. A. Mangi, M. H. W. Ibrahim, N. Jamaluddin, M. F. Arshad, S. A. Memon, S. Shahidan and R. P. Jaya. *Coal bottom ash as a sustainable supplementary cementitious material for the concrete exposed to seawater*. in *AIP Conference Proceedings*. 2019. AIP Publishing LLC.
- 933
934
- 935 [101] T. Jena and K. Panda, *Compressive strength and carbonation of sea water cured blended concrete*. Int. J. Civil Eng. Technol, 2017. **8**(2): p. 153-162.
- 936
937 [102] R.-j. Liu, Q.-j. Ding, P. Chen and G.-y. Yang, *Durability of concrete made with manganese slag as supplementary cementitious materials*. Journal of Shanghai Jiaotong University (Science), 2012. **17**(3): p. 345-349.
- 938
939
- 940 [103] E. Ganjian and H. S. Pouya, *Effect of magnesium and sulfate ions on durability of silica fume blended mixes exposed to the seawater tidal zone*. Cement and concrete research, 2005. **35**(7): p. 1332-1343.
- 941
942
- 943 [104] A. Memon, S. Radin, M. Zain and J.-F. Trottier, *Effects of mineral and chemical admixtures on high-strength concrete in seawater*. Cement and Concrete Research, 2002. **32**(3): p. 373-377.
- 944
945 [105] M. W. Ibrahim, A. Hamzah, N. Jamaluddin, S. Mangi and P. Ramadhansyah, *Influence of bottom ash as a sand replacement material on durability of self-compacting concrete exposed to seawater*. Journal of Engineering Science and Technology, 2020. **15**(1): p. 555-571.
- 946
947
- 948 [106] W. Wang, S. Xu, Q. Li and S. Dong, *Long-term performance of fiber reinforced cementitious composites with high ductility under seawater attack with different salinities*. Construction and Building Materials, 2022. **317**: p. 126164.
- 949
950
- 951 [107] D. Ramachandran, R. George, V. Vishwakarma and U. Kamachi Mudali, *Strength and durability studies of fly ash concrete in sea water environments compared with normal and superplasticizer concrete*. KSCE Journal of Civil Engineering, 2017. **21**(4): p. 1282-1290.
- 952
953
- 954 [108] R. Kumar, M. Verma and N. Dev, *Investigation on the Effect of Seawater Condition, Sulphate Attack, Acid Attack, Freeze-Thaw Condition, and Wetting-Drying on the Geopolymer Concrete*. Iranian Journal of Science and Technology, Transactions of Civil Engineering, 2021: p. 1-31.
- 955
956
- 957 [109] S. Tome, A. Nana, C. R. Kaze, J. N. Y. Djobo, T. Alomayri, E. Kamseu, M.-A. Etoh, J. Etame and S. Kumar, *Resistance of Alkali-Activated Blended Volcanic Ash-MSWI-FA Mortar in Sulphuric Acid and Artificial Seawater*. Silicon, 2021: p. 1-8.
- 958
959
- 960 [110] N. Zhang, A. Hedayat, L. Figueroa, K. X. Steirer, H. Li, H. G. B. Sosa, R. P. H. Bernal, N. Tupa, I. Y. Morales and R. S. C. Loza, *Experimental studies on the durability and leaching properties of alkali-activated tailings subjected to different environmental conditions*. Cement and Concrete Composites, 2022. **130**: p. 104531.
- 961
962
- 963 [111] D. Bondar, C. J. Lynsdale, N. B. Milestone and N. Hassani, *Oxygen and chloride permeability of alkali-activated natural pozzolan concrete*. ACI Materials Journal, 2012. **109**(1): p. 53-61.
- 964
965

- 966 [112] O. Ojedokun and P. Mangat, *Chloride diffusion in alkali activated concrete*, in *II International*
1 967 *Conference on Concrete Sustainability - ICCS16*. 2016, International Center for Numerical Methods in
2 968 Engineering (CIMNE).
- 3 969 [113] M. Z. Y. Ting, K. S. Wong, M. E. Rahman and S. J. Meheron, *Deterioration of marine concrete*
4 970 *exposed to wetting-drying action*. *Journal of Cleaner Production*, 2021. **278**: p. 123383.
- 5 971 [114] H. Haynes, R. O'Neill, M. Neff and P. K. Mehta, *Salt weathering distress on concrete exposed to*
6 972 *sodium sulfate environment*. *ACI Materials Journal*, 2008. **105**(1): p. 35.
- 7 973 [115] M. Khatibmasjedi, S. Ramanathan, P. Suraneni and A. Nanni, *Compressive strength development*
8 974 *of seawater-mixed concrete subject to different curing regimes*. *ACI Materials Journal*, 2020. **117**(5).
- 9 975 [116] X. Tang, Q. Xu, K. Qian, S. Ruan, S. Lian and S. Zhan, *Effects of cyclic seawater exposure on the*
10 976 *mechanical performance and chloride penetration of calcium sulfoaluminate concrete*. *Construction*
11 977 *and Building Materials*, 2021. **303**: p. 124139.
- 12 978 [117] J. Wu, H. Li, Z. Wang and J. Liu, *Transport model of chloride ions in concrete under loads and*
13 979 *drying-wetting cycles*. *Construction and Building Materials*, 2016. **112**: p. 733-738.
- 14 980 [118] J. Bao and L. Wang, *Combined effect of water and sustained compressive loading on chloride*
15 981 *penetration into concrete*. *Construction & building materials*, 2017. **156**: p. 708-718.
- 16 982 [119] H. Li, J. Wu, Y. Song and Z. Wang, *Effect of External Loads on Chloride Diffusion Coefficient of*
17 983 *Concrete with Fly Ash and Blast Furnace Slag*. *Journal of materials in civil engineering*, 2014. **26**(9): p.
18 984 4014053.
- 19 985 [120] D. H. Kim, K. Shimura and T. Horiguchi, *Effect of Tensile Loading on Chloride Penetration of*
20 986 *Concrete Mixed with Granulated Blast Furnace Slag*. *Journal of Advanced Concrete Technology*, 2010.
21 987 **8**(1): p. 27-34.
- 22 988 [121] S.-W. Yoo and S.-J. Kwon, *Effects of cold joint and loading conditions on chloride diffusion in*
23 989 *concrete containing GGBFS*. *Construction & building materials*, 2016. **115**: p. 247-255.
- 24 990 [122] D.-y. Yang and J.-j. Luo, *The damage of concrete under flexural loading and salt solution*.
25 991 *Construction and Building Materials*, 2012. **36**: p. 129-134.
- 26 992 [123] Q.-f. Liu, Z. Hu, X.-e. Wang, H. Zhao, K. Qian, L.-j. Li and Z. Meng, *Numerical study on cracking*
27 993 *and its effect on chloride transport in concrete subjected to external load*. *Construction & building*
28 994 *materials*, 2022. **325**.
- 29 995 [124] F. Liu, Z. You, A. Diab, Z. Liu, C. Zhang and S. Guo, *External sulfate attack on concrete under*
30 996 *combined effects of flexural fatigue loading and drying-wetting cycles*. *Construction and Building*
31 997 *Materials*, 2020. **249**: p. 118224.
- 32 998 [125] M. Z. Y. Ting, K. S. Wong, M. E. Rahman and M. S. Joo, *Cyclic compressive behavior of limestone*
33 999 *and silicomanganese slag concrete subjected to sulphate attack and wetting-drying action in marine*
34 1000 *environment*. *Journal of Building Engineering*, 2021. **44**: p. 103357.
- 35 1001 [126] O. S. B. Al-Amoudi, M. Maslehuddin, M. Shameem and M. Ibrahim, *Shrinkage of plain and silica*
36 1002 *fume cement concrete under hot weather*. *Cement and Concrete Composites*, 2007. **29**(9): p. 690-699.
- 37 1003 [127] A. Farahani, H. Taghaddos and M. Shekarchi, *Prediction of long-term chloride diffusion in silica*
38 1004 *fume concrete in a marine environment*. *Cement and Concrete Composites*, 2015. **59**: p. 10-17.
- 39 1005 [128] A. Dousti, R. Rashetnia, B. Ahmadi and M. Shekarchi, *Influence of exposure temperature on*
40 1006 *chloride diffusion in concretes incorporating silica fume or natural zeolite*. *Construction and Building*
41 1007 *Materials*, 2013. **49**: p. 393-399.
- 42 1008 [129] L.-c. Wang and T. Ueda, *Meso-scale modeling of chloride diffusion in concrete with consideration*
43 1009 *of effects of time and temperature*. *Water Science and Engineering*, 2009. **2**(3): p. 58-70.
- 44 1010 [130] Z. Chen, P. Huang, G. Yao, X. Guo, Y. Yang, W. Li and B. Wu, *Experimental study on fatigue*
45 1011 *performance of RC beams strengthened with CFRP under variable amplitude overload and hot-wet*
46 1012 *environment*. *Composite Structures*, 2020. **244**: p. 112308.
- 47 1013 [131] M. Sahmaran, T. K. Erdem and I. O. Yaman, *Sulfate resistance of plain and blended cements*
48 1014 *exposed to wetting–drying and heating–cooling environments*. *Construction and Building Materials*,
49 1015 2007. **21**(8): p. 1771-1778.

1016 [132] Y. Wang, G. Fang, W. Ding, N. Han, F. Xing and B. Dong, *Self-immunity microcapsules for corrosion*
1 1017 *protection of steel bar in reinforced concrete*. Scientific reports, 2015. **5**(1): p. 1-8.
2 1018 [133] M. A. DeRousseau, J. R. Kasprzyk and W. V. Srubar Iii, *Computational design optimization of*
3 1019 *concrete mixtures: A review*. Cement and Concrete Research, 2018. **109**: p. 42-53.
4 1020 [134] Z. Zhu and I. Brilakis, *Comparison of optical sensor-based spatial data collection techniques for*
5 1021 *civil infrastructure modeling*. Journal of Computing in Civil Engineering, 2009. **23**(3): p. 170-177.
6
7
8 1022
9
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